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ALVIN TEPO TOGBA

TECHNO-ECONOMIC ANALYSIS OF HYBRID ENERGY SYSTEM FOR RURAL ELECTRIFICATION IN LIBERIA

Defended on 20/09/2020 Before the Following Committee:

Chair : Pr. Angeles López Agüera (University of Santiago de Compostela, Spain)

Supervisor: Prof. Amine Boudghene Stambouli

External Examiner: Dr.-Ing. habil. Kokouvi Edem N'TSOUKPOE (2iE, Burkina Faso)

Internal Examiner: Dr. Amazigh Dib (PAUWES, Tlemcen, Algeria)

PAN AFRICAN UNIVERSITY INSTITUTE OF WATER AND ENERGY SCIENCES (INCLUDING CLIMATE CHANGE)

ENERGY ENGINEERING

MASTER THESIS

TOPIC**:**

TECHNO-ECONOMIC ANALYSIS OF HYBRID ENERGY SYSTEM FOR RURAL ELECTRIFICATION IN LIBERIA

CASE STUDY: SOUTHEASTERN REGION, LIBERIA, WEST AFRICA

SUPERVISOR: PROF. AMINE BOUDGHENE STAMBOULI

PREPARED BY: ALVIN TEPO TOGBA

Supervisor **Student:**

DEDICATION

This Masters Dissertation is dedicated especially to you my most beloved, my Sun and Stars, Moon of my Life, my grandmother Beatrice M. Boe, my foster father Mark Dykstra, my love ones who has always given me every support I could possible hope for in this journey.

STATEMENT OF THE AUTHOR

I, Alvin Tepo TOGBA hereby declare that this thesis represents my original work and it has not been submitted to another institution for the award of a degree, diploma, or certificate. I also declare that all words and ideas from other works presented in this thesis have been duly cited and referenced in accordance with the academic rules and regulations.

STUDENT:

Name: Alvin Tepo TOGBA Signature:

Date: /09/2020

Academic Unit: Energy (Engineering

Track) PAU Institute: PAUWES

SUPERVISOR:

Name: Prof. Amine Boudghene STAMBOULI Signature:

Date: / 09/2020

ABSTRACT

Rural Electrification in West Africa has remained a challenge for the growth and development of the region. The Economic Community of West African States (ECOWAS) has set a target of 2030 to achieve approximately 100% electrification in all member countries. Liberia is one of the least electrified countries globally and in the region, where only 19 % of the population has access to electricity, with rural electrification rate just at 1%.

According to the roadmap for Energy Access in Liberia, the existing reference framework in the field of energy policy, the government of Liberia has set a target of 60 % of total primary energy supply from renewable energy in the electricity mix by 2030. The objectives envisioned by the government are to reach an overall national electrification rate of 65% with an urban electrification rate of 85 % and 40 % for the rural case by 2030.

The study presents a conceptualization of the techno-economic feasibility of integrating RETs into the national grid with case study of pump hydro storage (PHS) and electric batteries with solar photovoltaic (PV) in Liberia. The results are explored for an off grid standalone PV plus storage system for a rural setting and a grid connected PV system for an urban setup. The least cost configurations for both the cases are determined using HOMER (Hybrid Optimization Model for Electric Renewables). The results highlight and outstates the need of extended solar penetration in Liberia in response to the challenges of low electrification rates in the country.

PV plus pumped hydro storage remains the optimal system architecture as compared to PV plus electric batteries for off grid standalone systems provided the geographic availability of lower and upper reservoirs. The capital cost of PV remains to be the most dominating factor in the cost of optimal system for both the urban and the rural cases, and driving down the costs of PV would have the most positive effect for increased electricity access in the country.

RÉSUMÉ

L'électrification rurale en Afrique de l'Ouest est restée un défi pour la croissance et le développement de la région. La Communauté économique des États de l'Afrique de l'Ouest (CEDEAO) a fixé un objectif de 2030 pour atteindre environ 100% d'électrification dans tous les pays membres. Le Libéria est l'un des pays les moins électrifiés du monde et de la région, où seulement 19% de la population a accès à l'électricité, avec un taux d'électrification rurale de 1% seulement.

Selon la feuille de route pour l'accès à l'énergie au Libéria, le cadre de référence existant dans le domaine de la politique énergétique, le gouvernement du Libéria s'est fixé un objectif de 60% de l'approvisionnement total en énergie primaire à partir d'énergies renouvelables dans le mix électrique d'ici 2030. Les objectifs envisagés par le gouvernement sont d'atteindre un taux national d'électrification global de 65% avec un taux d'électrification urbaine de 85% et de 40% pour le cas rural d'ici 2030.

L'étude présente une conceptualisation de la faisabilité technico-économique de l'intégration des TER dans le réseau national avec une étude de cas du stockage hydraulique par pompe (PHS) et des batteries électriques avec solaire photovoltaïque (PV) au Libéria. Les résultats sont explorés pour un système de stockage PV plus autonome hors réseau pour un environnement rural et un système PV connecté au réseau pour une installation urbaine. Les configurations les moins coûteuses pour les deux cas sont déterminées à l'aide de HOMER (Hybrid Optimization Model for Electric Renewables). Les résultats soulignent et démontrent la nécessité d'une pénétration solaire étendue au Libéria en réponse aux défis des faibles taux d'électrification dans le pays.

Le stockage hydroélectrique photovoltaïque plus pompé reste l'architecture de système optimale par rapport aux batteries photovoltaïques plus électriques pour les systèmes autonomes hors réseau, à condition de la disponibilité géographique des réservoirs inférieurs et supérieurs. Le coût en capital du PV reste le facteur le plus dominant du coût d'un système optimal pour les cas urbains et ruraux, et réduire les coûts du PV aurait l'effet le plus positif pour un accès accru à l'électricité dans le pays.

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Sincere gratitude goes to the Pan African University and the African Union Commission, which sponsored my education at PAUWES and also provided funds for this research. I am deeply grateful to my supervisor, Professor Amine Boudghene STAMBOULI, whose guidance and insightful contributions led to the successful completion of this thesis.

Heartfelt thanks to the entire leadership especially Director Stephen Potter at Liberia Rural and Renewable Energy Agency (LRREA), and staff members of EnDev Liberia and the LEC sub office in Zwedru Rural Liberia who have been so helpful during the scope of my internship first phase and data collection in Rural Liberia.

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LIST OF ABBREVATIONS

AC	Alternating Current
AfDB	African Development Bank
AfT	Agenda for Transformation
AU	African Union
CLSG	Cote D'Ivoire, Liberia, Sierra Leone, Guinea
COE	Cost of Energy
CO2	Carbon dioxide
DC	Direct Current
ECOWAS	Economic Community of West African States
HOMER	Hybrid Optimization Model for Electric Renewables
HRES	Hybrid Renewable Energy System
HES	Hybrid Energy System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
Ktoe	Kilo Tons of Oil Equivalent
kVA	Kilovolt Ampere
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt peak
LCOE	Levelized Cost of Electricity
LEC	Liberia Electricity Corporation
MLME	Ministry of Lands, Mines and Energy
MRU	Mano River Union
NEC	National Energy Committee
NEP	National Energy Policy
O&M	Operating and Maintenance cost
PHS	Pump Hydro Storage Photovoltaic
PV	Photovoltaics
WAPP	West African Power Pool

LIST OF TABLES

TITLE OF TABLE ***Page***

LIST OF FIGURES

Figure Number **Content** **Page**

Table of Contents

CHAPTER ONE

1 INTRODUCTION

Access to modern energy for electricity and clean cooking methods in sub-Sahara Africa countries remains a big challenge. Millions of people in the world today lack access to reliable and sustainable energy services especially those for those living in remote areas. The challenges are due to poor transmission and distribution networks, poor terrines, scattered population and low income of the dwellers. The integration of Hybrid Energy Systems (HES) offers a unique opportunity which serves as a solution to decentralized rural electrification services. HES have proven to be a suitable option for electricity generation and production in many decentralized rural communities in the world.

While the global access to electricity has increased over the past two decades, there are some parts of the world that still lack the access to electrical energy. This greatly limits growth opportunities and severely affects all aspects of the society. The situation seems to be critical in some West African countries but is changing quite rapidly [1]. By 2030, the ECOWAS (Economic Community of West African States) aims to achieve 100 % electrification in all of its 15 member states [2].

The lack of grid infrastructure only makes the situation worse. According to the roadmap for Energy Access in Liberia, the existing reference framework in the field of energy policy, the government of Liberia has set a target of 60 % of total primary energy supply from renewable energy in the electricity mix by 2030. The objectives envisioned by the government are to reach an overall national electrification rate of 65% with an urban electrification rate of 85 % and 40 % for the rural case by 2030.
To achieve these goals, a study by the Endev/LRREA funded by the European Commission and GIZ suggests that smaller local electrification projects based on indigenous renewable source like standalone PV in the long term are expected to be more feasible than centralized ones based on fossil fuels. The study also suggests that 65% of the non-electrified settlements need to be served by decentralized power plants which make it an ideal choice since grid extension is considered highly expensive by the government.

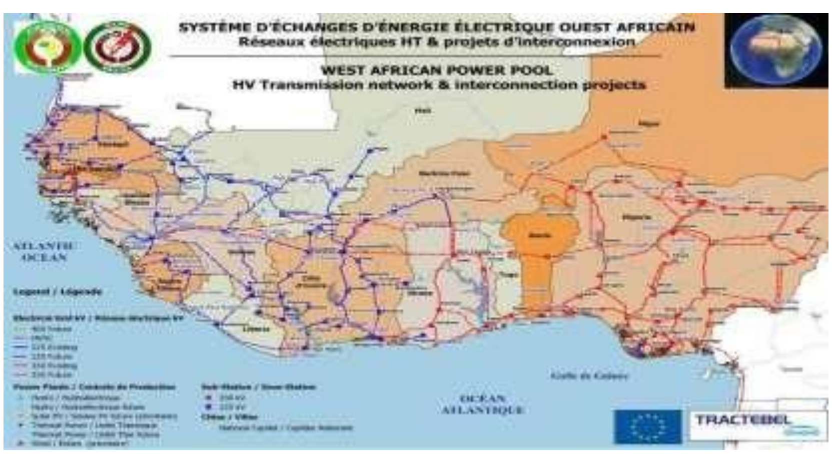


Figure 1. Grid Connections in West Africa [4]

Several projects have been proposed by Economic Community of West African States (ECOWAS) to make use of this solar potential for electrification of the region. ECOWAS in 2006 started an initiative called the West African Power Pool (WAPP) to promote cooperation and integration of national power systems of fourteen inland countries in West Africa into a unified electricity market. ECOWAS and WAPP in 2012 approved a list of 59 priority projects for the region adopted from the Master Plan for the Generation and Transmission of Electrical Energy prepared by Tractebel [3]. Liberia is one of the 15 member state of the West African Power Pool. WAPP has proposed many solar projects in the country. One of the project is an installation of the 92 MW Hydro plant in the country and 6 other other identified sited to be planted by 2024, the project has IRENA (International Renewable Energy Agency), World bank, EU and AfD (Abu Dhabi Fund for Development) as copartners.

Decentralized energy projects could play a huge role in the rapid electrification of the nation. One of the key components of decentralized systems is storage. The role of energy storage, in enabling the penetration of renewables is increasingly becoming paramount, given the continuous decreasing trend in the capital prices of Li-ion batteries [5]. Figure 2 shows the projected decrease in the capital cost of Li- ion batteries from 600 $/kWh in 2016 to about 200 $/kWh in 2030 through improvements in the value chain processes.

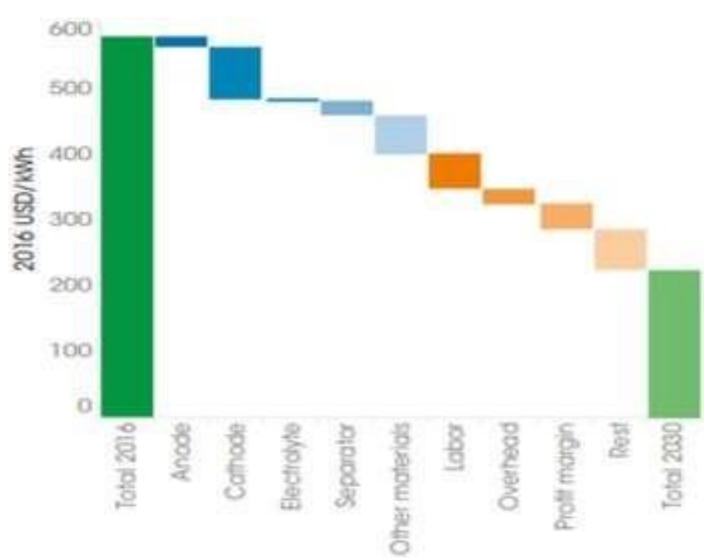


Figure 2. Decreasing Cost of Li-ion Batteries [5]

Pumped hydro storage (PHS) is undoubtedly the most mature kind of storage technology with a large lifetime of 25-100 years [5], [7]. In Europe, PHS represent 99 % of the grid connected storage that are employed for a wide range of operations like load shifting, regulation reserve voltage support etc. [8]. Overall, as per IEA projections [9], the global PHS capacity is to increase almost by around 20 % (29 GW) in the next five years whereas a total of 1.3 GW of PHS was added in 2016-2017 for the sub Saharan African region [9].

1.1 Background of Study

The objective of this study is to assess the techno-economic, environmental and social impacts on the usage of existing hybrids as well as hybrid planned to operate in the near future in Liberia, using the work of Energizing Development (Endev-Liberia) as a bench mark for case study judging by how progressive their work in the renewable energy sector has been in rural Liberia.

The methodology for this study is based on reviewing the energy situation in Liberia and a vivid literature review on existing approaches in energy production in decentralized communities where hybrid systems were installed, as well as secondary data being collected from the Liberia Rural and Renewable Energy Agency (LRREA) and the Liberia Electricity Cooperation (LEC), Environmental Protection Agency (EPA) of Liberia.
Hybrid Optimization Model for Electric Renewables (HOMER) software will be used for simulating and optimizing the cost of electricity production, solar energy fraction and carbon dioxide emissions from the hybrid systems used in rural electrification as well as determining which hybrid is most appropriate based on the techno-economic analysis carried on; that is situating the specific rural part of Liberia, analyzing the renewables potential that are exploitable and then harnessing all possible source of energy for providing solutions to the enormous energy problems faced by inhabitants of Southeastern Liberia.

The research will use data collected through interviews and questionnaires to determine the relationship between stakeholder participation in policy making and policy success. The study hopes to show that limited stakeholder participation in policy making and government reliance on grid extension has been the major barrier to rural electrification. There is therefore need for the Liberian rural electrification agency to establish programs that will foster the quick impact development of offgrid hybrids for residents in rural areas.

The significance of this study is to carry out an assessment on performance of hybrid system to ensure reliability and sustainability in electricity generation for rural electrification in the Liberian context. The expected outcomes of this research will be focused on providing recommendations and strategies that the Liberia Rural and Renewable Energy Agency (LRREA), NGOs in the energy sector and Liberia Electricity Cooperation (LEC) can use to improve the expansion of rural electrification in Liberia.

1.2 Problem Statement

Approximately 1.2 billion people are without access to electricity in the world (which is about 16% of the global population in 2018) and roughly about 600 million people live without electricity in the sub-Sahara Africa and most of them live in rural areas. [10] One of the most critical inputs towards development in any nation is electricity, it is considered as the main infrastructural requirements for agricultural, industrial and social- economic development. [11] It is estimated that 85% of the 1.2 billion people in the world living without access to electricity reside in rural areas, which is attributed to the marginalization of the poor as well as their long distance from established electrical grids [12].

Electricity being an input of production contributes significantly to the well-being of the population whereby providing goods and services to meet their desired need. Lack of access to electricity in developing countries serves as a major barrier to poverty reduction and economic development [13].According to (ECREEE, 2018) [14] the major challenge for economic growth and social development in West Africa is related to energy poverty. poverty in the region. Sub Saharan Africa has 588 million people without access to electricity and has the highest rate of persons without access worldwide (IEA, 2016) [15].

Rural renewable electrification in Liberia is a key component for the development of the country, something which national government needs to pay more attention to in striving for development and improvement of livelihood of citizens. Access to electricity in Liberia is a major challenge in terms of production/generation, transmission & distribution and consumption. Electrification rate in Liberia is very low when compared to many countries in the world with a total access rate of just 21.4% in 2019 with the electrification access rate having urban and rural access around 80% and 20% respectively [16].

According to the data of the government and World Bank, about 16.8% of urban residents and less than 2% of rural residents have currently electricity access that is connected to the national grid. Other source of power is largely from self-generation with gasoline or diesel generators using expensive imported fuel since the country imports all petroleum products. This is where the usage of hybrid renewable energy system is cardinal, and comes in handy. This situation affects most people especially for those living in rural areas where there is almost no access to electricity due to lack of grid power connecting systems and off-grid power systems have not been fully developed in most of these areas.

In addition, the grid-connected sites in southeastern Liberia are plagued with incessant power outages and poor performance of the grid during the rainy seasons, where huge transmission losses are faced. There is also the problem of little or no availability of the national grid. Micro grid system is found to be the best solution for rural electrification, since it can be on- or off grid-connected. This work aims to conduct the techno-economic feasibility of Hybrid Energy system (HES) for a village in Grand Gedeh County, Southeastern Liberia.

The migration from conventional sources of energy has resulted in growing worldwide interest to Renewable Energy Sources (RES). Renewable energy plays an intense role in mitigating global GHG emission by drastically lowering the emissions profile of the global system (IRENA, 2017b). Sub-Sahara Africa is endowed with many renewable energy resources that offer an opportunity in electricity generation in rural areas.

Major source of energy in rural and some urban communities in Liberia is from traditional use of biomass (firewood, charcoal), especially for cooking. The high demand for solid biomass for cooking purposes have an impact on the natural vegetation such as deforestation which results to a decrease in rainfall in the region (Azoumah et al., 2011) [17]. For the purpose of lighting, most people highly depend on candles, oil lamps, dry- cell battery lamps and small thermal diesel generators.

Each year, approximately 4.3 million premature deaths occur due to household air pollution exacerbated by burning solids the traditional way and the usage of generators. Without access to sustainable energy, development goals cannot be achieved (IEA, 2017). Access to electricity is particularly crucial to human development, as certain basic activities—such as lighting, refrigeration, running household appliances, and operating equipment—cannot be easily carried out using other forms of energy [18]. The migration from conventional sources of energy has resulted in growing worldwide interest to Renewable Energy Sources (RES). Renewable energy plays an intense role in mitigating global GHG emission by drastically lowering the emissions profile of the global system. Sub-Sahara Africa is endowed with many renewable energy resources that offer an opportunity in electricity generation in rural areas.

In Liberia, although there are a few potential of renewables the nation lacks, but there is also high potentials of renewables of Hydro, Solar and Biomass which can be quickly harnessed for energy generation. The Liberian nation has an enormous amount of untapped hydro potential amounting somewhere to about 1,500MW- 2,300MW, as stated by the Liberia National Investment Commission [19]. Liberia also has several river sites within the country that hold hydro power potential some are being exploited and some are yet to be tapped. But they are often at a smaller scale [20].

Rural areas of Liberia are generally not connected to the grid at all. Solar power generation is a great option for hard-to¬ reach areas where connecting to a local power station is not an option either. Solar power generation options are most viable in combination with storage systems, as peak use of electricity does not coincide with daylight. Through storage systems the dip in power generation throughout the rainy season can also be mitigated [21].

1.3 Research Questions

To address the problem highlighted in this study, the following question will guide this study:

1. Can the micro-grid (hybrid energy system), consisting of renewable energy resources and the available potential provide continuous and sustainable power to rural Liberian communities?
2. What parameters or components should be considered when designing PV solar based hybrid systems for rural Liberians?
3. To what extent is the suggested hybrid energy system able to be competitive with systems running on only non-renewables?
4. To what extent has the Liberian Rural and Renewable Energy Agency been effective in implementing standalone hybrids for people with zero access to electricity?
5. What contribution will the hybrid energy system bring to the economy and what are the likely environmental and social impacts?
6. How is the government utility LEC (Liberian Electricity Cooperation helping in the promotion of rural electrification especially to places where the grid are no reaching?

1.4 Research Objectives

The main objective of this work is to assess the techno-economic analysis of using solar PV based hybrid system for efficient energy utilization for rural households in Liberia.
Specific Objectives

- ✓ Identifying the existing approaches for decentralized electricity production being used.
- ✓ To come up with the least cost hybrid HES suitable for rural electrification and that which delivers enough energy to attain a prescribed degree of supply reliability for rural households and homesteads
- ✓ To develop an economic cost model for the systems
- ✓ Perform techno-economic analysis and Greenhouse gases emission from the power plant using HOMER as the modeling tool and identifying the existing approaches for decentralized electricity production.

1.5 Scope of the Study

Cavalla village situated in Maryland was selected as a case study for this work due to the high speed flow of the Cavalla River and the considerable solar irradiation in the location. The community is selected due to constant power shortage and poor performance of the grid especially during summer season weak inaccessibility to the grid. The energy solutions are limited to off-grid renewable energies/fuel plants.

CHAPTER TWO

2 LITERATURE AND TECHNICAL REVIEW

This chapter gives detail review on literature related to the subject under discussion and technical insights of other related projects that have been carried on using HES and power storages. The chapter outlines the study site and area of case study accessing the potential of energy et al.

2.1 Geographical and Climatic Overview of Liberia

Liberia is a Sub-Saharan nation in West Africa located at 6 °N, 9 °W. It borders the north Atlantic Ocean to the southwest (580 kilometres (360 mi) of coastline) and three other African nations on the other three sides, Sierra Leone to the northwest, Guinea to the northeast and Ivory Coast (Cote d'Ivoire) to the east. In total, Liberia comprises 110,000 square kilometres (43,000 sq mi) of which 96,300 square kilometres (37,190 sq mi) is land and 15,000 square kilometres (5,810 sq mi) is water.

2.1.1 The Economic Situation in Liberia

Liberia's economy relies traditionally on forestry (rubber and timber) and mining (gold, diamonds, and iron ores) as major sources of income. The mining sector along employs more than 100,000 people and has the potential to generate income and help reduce unemployment, estimated at 25%. Agriculture employs an estimated 0%of population, mainly youth and women (African Development Bank Outlook 2019) [22]. Liberia's economy has face uncertainty in the past two years due to declining mining exports and rising inflation and currency depreciation. Real GDP growth after declining to 0.4% in 2019 is expected to recover to 1.6% in 2020 underpinned by mining, forestry and agriculture (AFDB 2020). Liberia GDP stands at 3.264 billion USD and 455USD GDP per capita (2018 World Bank Outlook). The figure below shows the annual GDP of Liberia with yellowish line representing its annual growth rate.

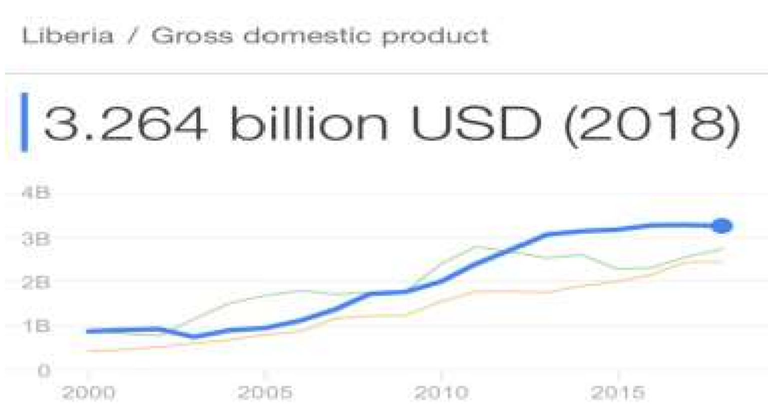


Figure 3. GDP of Liberia 2018, Source World Bank

2.1.2 Primary Energy Consumption in Liberia

Traditional biomass such as firewood, charcoal, and wood fuel are the most common energy sources consumed by households for cooking purpose in both rural and urban areas in Liberia. Many rural populations heavily rely on jo-fire (a kernel oil run light), lantern, candles, and other environmentally unsafe lighting systems. Biomass accounts for about 80% of the total energy consumption, followed by petroleum products and electricity 16% and 2% respectively

2.2 Renewable Energy Resources in Liberia

2.2.1 Solar Potential in Liberia

Liberia is located near to the equator, creating conditions that are favorable for the use of solar radiation for generation of energy. Both hydro and solar powers have great potential, but since the weather alternates so drastically between the dry and rainy seasons, the two sources of energy have their peaks at different times of the year.

Satellite measurements point to a monthly average daily solar radiation between 6.02kWh/m2/d in the months of February to March, and 3.85kWh/m2/day between the months of July and August. This means great prospects for photovoltaic systems, especially in the dry season. This high and consistent potential for solar energy across the country adds to an average level of 1,712kWh/m2/year, which could generate 1,400 to 1,500kWh/kWp. The Liberia National Investment Commission (LNIC) sees a peak total production of 1400-1700 kWh (including losses) as a realistic, untapped potential.

Rural areas of Liberia are generally not connected to the grid at all. Solar power generation is a great option for hard-to¬ reach areas where connecting to a local power station is not an option either. Solar power generation options are most viable in combination with storage systems, as peak use of electricity does not coincide with daylight. Through storage systems the dip in power generation throughout the rainy season can also be mitigated [23].

Figure 4. Solar Photovoltaic Power Potential of Liberia [23]

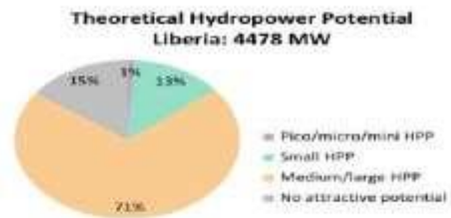
2.2.2 Hydro Potential

Regarding hydro, the Liberian nation has an enormous amount of untapped hydro potential amounting somewhere to about 1,500MW- 2,300MW, as stated by the Liberia National Investment Commission [24]. This potential of electricity however varies between Rainy and Dry season.

Liberia has an average rainfall per annum of 4624mm in its capital, considering it the city with the highest rainfall on Earth. Liberia like most West African states has just two seasons, Rainy and Dry. And its rainy seasons falls in between the Months of May to September, where the peak of rainfall is often in August and September. On an overall average, Liberia can be said to receive 0.1mm of rain within 182days of every year[25].

Currently, the Mount Coffee Hydroplant is the only generator of hydropower in the country. Since completion of the dam, the constructions of storage facilities upstream have come underway. These storage facilities are meant to sustain the generation of energy by the dam throughout the dry season. Constructing hydro plants is capital intensive, but once they are in place they are cheap and easily maintainable.

According to the Liberia National Investment Commission, the potential hydropower capacity in Liberia reaches up to 1,500MW[15]. Close consideration of the following elements are necessary when thinking of working in hydropower in Liberia: the suitability of hydropower plants with and without reservoirs, verification of technical and hydraulic data, integration into the transmission grid and environmental and social impacts. Some of the country's biggest rivers are Border Rivers and therefore demand a regional approach. The Agenda for Transformation identified the Cavalla River, the St.John River and the St.Paul River as potential sites for hydroelectricity projects. [24] The country also offers several sites which hold small hydro power potential. [25] [26]



Theoretical Hydropower Potential of Rivers in Liberia	
Pico/micro/mini HPP	47 MW
Small HPP	592 MW
Medium/large HPP	3164 MW
No attractive potential	675 MW
Total of all rivers in country	4478 MW
Total of rivers with attractive theoretical potential for pico/micro/mini, small, or medium/large HPP	3803 MW

Figure 5 (a) Theoretical Hydro Potential of Liberia [24] (b) Liberia Hydro Potential Map [25]

2.2.3 Wind Potential

Based on wind speed data which was made available globally, the estimated speed of the wind in Liberia's coastal areas is approximately 3.5,/s to 6 m/s, depending on the month of the year [27]. Windmills have the potential to be used throughout the country; especially turbines specialized for low wind speeds. Higher wind speeds in the coastal areas provide a good source of energy in specific months, while the constant wind speed in the more mountainous, rural areas are more reliable throughout the year.

2.2.4 Biomass Potential

Waste to Energy

Municipal Solid Waste (MSW) is an untapped source of energy generation in Liberia. According to a 2012 study, waste generation in Liberia lay at 164 kg/capita in 2012, with estimated projections for dramatic increases over the coming 13 years. [28] The dense population of the capital city of Monrovia has created a municipal waste disposal crisis. Organizations such as the Gates Foundation, UNICEF and the World Bank [29] have attempted to tackle this issue. Converting the waste into energy may turn it from a burden into a renewable energy solution. Turning waste into a commodity will provide an incentive for citizens to properly dispose of their waste.

Waste generation 2012 (kg/capita)	164
Estimated waste generation 2025 (kg/capita)	256
Waste generation (10^3 t/year)	339
Estimated waste generation 2025 (10^3 t/year)	814
Waste collection (10^3 t/year)	135
Estimated waste collection 2025 (10^3 t/year)	489

Figure 6. Biomass Potential Evaluation of Liberia [25]

2.3 Renewable Energy Strategy and Policy in Liberia

The lack of energy infrastructure development since the end of the civil has been identified by the Liberian government as a key limiting factor to the nation's economic growth. The expansion of this infrastructure has become a priority within the region, supported by the West African Power Pool (WAPP) and its 2000 Master Plan. Liberia, as a nation, has stipulated in its National Energy Policy that by 2030 they aim to provide access to energy to 70% of the population of Monrovia and 35% of the population as a whole. The recent rehabilitation of the Mount Coffee Hydro plant is a first clear step in the realization of these plans. [30]

The strategic objective of the Liberian government is to extend the grid throughout Monrovia and other urbanized areas. As the rural areas are sparsely populated, power can most easily be provided in those areas using small-scale thermal-, solar-and hydro-technologies. The need for more widespread and dependable energy provision means there are several business opportunities in the sector that are of immediate and high demand (immediate opportunities), whereas other solutions are very much viable but can be developed over the longer term (long-term opportunities) [31]. The goals set out by the National Energy Policy (NEP) aim to connect 70% of the Monrovia population and 35% of the nation as a whole by 2030.
New transnational endeavors are changing the energy sector in West Africa. In 1999, the West African Power Pool (WAPP) was created and in 2000 its Master Plan was put in place to provide energy throughout West Africa at an affordable price [32]. The Master Plan aimed to accelerate several regional interconnection line projects, one of which was a line to connect Cote D'Ivoire, Liberia, Sierra Leone and Guinea (CLSG). The CLSG project is a multinational investment operation and is financed by the World Bank, The European Investment Commission (EIB), the KfW and the African Development Bank (AfDB). This led to a Treaty being signed by the CLSG Head of State to establish a special purpose company called the Transmission Company Cote D'Ivoire, Liberia, Sierra Leone and Guinea (or TRANSCO CLSG). Getting connected to this transmission line is expected to have an extremely positive impact on the reliability and affordability of power in Liberia. The Ministry of Lands, Mines, and Energy (MLME) is currently implementing an Electricity Master Plan (EMP) to develop the energy sector.

2.3.1 POLICY FRAMEWORK

LIBERIA Agenda for Transformation (AfT)

The Agenda for Transformation as published on April 15th 2013 is the Government of Liberia's five-year development strategy. It sets up Liberia's long term vision of socio-economic transformation and development and articulates precise goals and objectives with corresponding interventions to move Liberia closed toward structural economic transformation. The 'Power and Energy' subsection (p.70) lays out the goals, constraints, objectives and agents for change identified for the energy sector. [33]

National Energy Policy (NEP)

The 'National Energy Policy: An Agenda for Action and Economic and Social Development' was developed by the Ministry of Lands, Mines and Energy and endorsed in 2009. It is the product of an extensive process of consultations that started with the National Energy Stakeholders Forum (NESF) in October of 2006. Recommendations from that forum were summarized, scrutinized and validated by all involved stakeholders, resulting in the NEP.

New Energy Act 2015

Also called the '2015 Electricity Law of Liberia', established the legal and regulatory framework for the generation, transmission, distribution and sale of electricity within Liberia. It also covers the import and export of power. The purpose of the law is to facilitate the implementation of the National Energy Policy.

Liberia is a member of ECOWAS and a signatory to the white paper for a regional policy on increasing access to energy services for rural and peri-urban populations, the Energy Protocol that outlines principles for cross-border energy trade and investment and the West African Power Pool (WAPP) to address the issue of power supply deficiency within West Africa. Additionally, Liberia is a signatory to the United Nations Framework Convention on Climate Change and its Kyoto protocol. Lastly, it has also joined the United Nations Sustainable Energy for All Initiative. In 2015, Liberia adopted the Electricity Law, which established the legal basis for public and private electricity service providers to offer commercial electricity service in Liberia, using grid expansion and offering off-grid service to rural and remote communities. According to the law, licenses for operation are to be issued by an independent regulator, the Liberia Electricity Regulatory Commission (LERC), which is also in charge of approving tariff setting methodologies. [34]

2.3.2 Rural Electrification in Liberia

Rural Energy Strategy and Master Plan for Liberia until 2030 made public in April 2016, the document presents Liberia's Rural Energy Strategy and Master Plan (RESMP) sets clear targets, identifies least-cost projects and technologies and proposes concrete investments for funding and implementation with appropriate institutional framework and capacity.

2.3.3 Formation of the Liberia Rural and Renewable Energy Agency

The Rural and Renewable Energy Agency (RREA) and the Renewable Energy Fund (REFUND), which up to this year (2015) was constituted through executive order in January 2010 that had to be renewed annually has now been enacted into law. The RREA's mandate includes integrating energy into rural development planning; promotion of renewable energy technologies; facilitating delivery of energy products and services through rural energy service companies (RESCOs) and community initiatives;

The RREA also has the mandate to facilitate and accelerate the economic transformation of rural Liberia by promoting the commercial development and supply of modern energy services to rural areas with an emphasis on locally available renewable resources. One of the RREA's principle functions is the planning and financing of rural energy projects for implementation by public, private and community developers. This includes educating the general public about renewable energy options and opportunities.

2.4.1 Electricity Access Rate and Real Electricity Price in Liberia

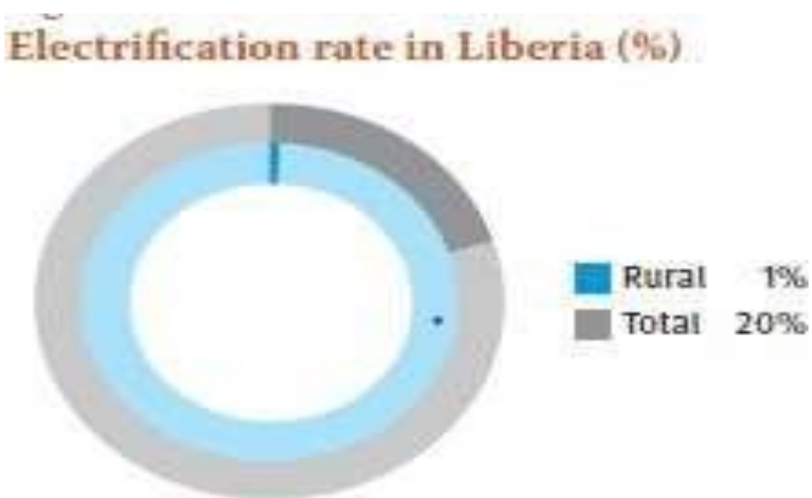


Figure 7. Electrification Rate in Liberia, [Retrieved from UNIDO 2018 SHP Report]

Electricity tariff constitutes fuel adjustment cost, generation tariff and Goods and Services Tax. The LEC tariff is regulated by the board of the LEC. A single tariff is applied for all types of consumers based on a revenue requirement approach, which considers the revenues needed to meet all the utility's operating expenses and capital costs. Tariffs are calculated quarterly, considering the price of equipment, service schedule, maintenance, distribution costs and 20 per cent of technical and non-technical losses. As of December 2017, the LEC tariff was 0.39 US$/kWh. The tariff was decreased from 0.49 US$/kWh in March 2017 in line with the Government's commitment to provide affordable electricity. [35]

2.4.2 Benefits of Rural Electrification

Rural Electrification plays a pivotal role in the socio-economic development of remote, isolated or less privileged communities worldwide. The impact of rural electrification on rural development has been discussed in many studies. Rural development is the process of improving the quality of life and economic well-being of people living in rural areas. Such areas are often relatively isolated and sparsely populated areas. Recent studies suggest that rural electrification has ripple effects on socio-economic development in rural areas.

According to Adu et al 2018 [34], when communities are connected to electricity, the initial effect is that households in such communities begin to purchase electrical appliances such as television sets, business equipment, These initial effects yield various infrastructure, access to information, and modernization of agriculture.

Adusah-Poku and Tekeuchi 2019 [35] add that in the medium term, these outputs also lead to more hours for studying, extended work times for shops and businesses and greater access to knowledge and information that has the potential to improve community welfare in the long run. In the Liberian contest this benefit has been attributed to the Liberia Rural and Renewable Energy Agency and the Rural Electrification Department of the Liberian Electrification Company.

Many nations regard rural electrification as a desirable investment with vast benefits for rural dwellers. So far, vast discussions have taken place concerning its cost, socio-economic and environmental merits [36]. These benefits span from increase in income levels with new work opportunities, welfare, technology and increased security and decrease infertility.

2.5 Technical Review

The literature on energy storage integration is dominated by optimal design studies with the purpose to identify the optimal size of storage. Cost is a primary concern when it comes to the deployment of storage especially in the developing countries. The World Bank group has recently committed 1 billion dollars to accelerate investments up to 4 billion dollars in the low-middle income countries under its program for "Accelerating Battery Storage for Development" and PV + storage is one of the key areas. [37].

Several studies have been performed to model energy storage systems for optimal cost benefits. In [38], G. Shrestha and L. Goel, have performed simulations for solar panel size and battery size to optimize the operation of a stand-alone PV system measures in terms of loss of load hours, the energy loss and the total cost. A study about battery storage in the developing countries [39] highlights the issues for investment. It states that for battery storage to be price competitive in the developing world, provide utility and drive private investments, "stacking of benefits and revenue streams" is needed. These can include mechanisms such as energy arbitrage and frequency containment reserves. These storage assets can be owned by market players that provide services that are procured by network operators. However, sizing is an important aspect when it comes to deploying these energy storage solutions. A study was performed by Nfah and Ngundam [40] on a hybrid configuration of pumped hydro, biogas, PV and a battery system for a village in Cameroon. The optimal configurations were determined and a cost of energy of 0.352 $/kWh was proposed using HOMER for optimization. Similarly, another study for a hybrid system design for remote areas in Ghana was performed by Adaramola et al. [41] to determine the techno-economic feasibility of wind – diesel generator and a solar hybrid system.

Sigarchian et al. [42] used HOMER to model the domestic sector of Kenya using a generation mix of PV/wind and biomass generation by using electric batteries as storage. Most of the other literature on hybrid renewable energy systems (HRES) in developing countries focus on electric batteries and several studies have been performed considering pumped hydro storage (PHS). Ma et al. [43] has used PHS for a commercial load with the objective of finding a feasible configuration using mathematical models. In the context of West Africa Daniel et al. [44] have performed an experimental and economical study of PV/diesel hybrid systems without storage for off grid areas. From the literature we can see that for optimization of hybrid systems, HOMER is a preferred choice. Also, the literature review shows that electric batteries have been considered extensively for standalone off grid applications but not much modelling has been done with PHS. There are some clear advantages of PHS such as lower life cycle cost as compared to batteries [42]. Also, there does not seem to be a study in literature on storage with PV in the context of Liberia. Hence, identifying the research gaps, for this study an analysis of PV + storage system for grid connected and off grid applications in Liberia is performed. In this study the COE and NPC of different combinations of PV, batteries and pumped hydro shall be determined using HOMER to compare these two storage options for techno-economic feasibility for grid connected and off grid operations in the context of Liberia.

2.5.1 Energy Modeling Tools

Driven by the technological improvements, falling costs, a proven track record, and growing recognition of the microgrid benefits [44], microgrids are progressively an option for electricity access in unelectrified areas in developing nations [45]. Hence, the increase of complexity of the microgrids caused by the intermittent nature of renewable generation as well as dynamic operating conditions of storage systems increased the need for microgrid simulation, sizing, and optimization tools [46]. Numerous tools emerged that can aid project planners in designing microgrids; they are based on a different programming language, and they can be either open-, closed- or closed-and-paid code [47].

2.5.2 Open Modeling Tools

The high cost of license and inability to customize the internal code leads to the adoption of more open-source energy modeling tools such as Oemof, Calliope, OSeMOSYS, and URBSS. Open source tools are therefore used [49]:

• To increase public transparency and public trust;

• For scientific reproducibility, and open development;

• For reduction of bottom-up planning barriers;

• To facilitate inclusive planning methods.

However, open-source modeling tools present some problems and barriers. First, most of the commercial and open-source codes available in the market are characterized by a limited number of components or offer limited complexity in the design of component models [50].

Further limitations are found in terms of user-friendliness or easy-to-use capabilities, such as an intuitive GUI as well as a complete, well-structured and accessible documentation [50]. Furthermore, a synonym of free-to-use so-called open-source models exist that are developed in programming languages, including the Generic Algebraic Modeling System (GAMS), or solved with proprietary solvers, that in both cases require license [50].

2.5.3 Closed Modeling Tools

Many closed-code commercial software tools are in the market; examples are like iHoga ®, PVSyst®, Polysun®, TRNSYS®. Other software with their details can be found in the following references [47][48]. The most commonly, proprietary software is Homer®. Homer is closedsource and paid software developed by the National Renewable Energy Laboratory (NREL) for both on-grid and off-grid systems. The large number of recently published studies that has performed optimization and sizing with Homer® highlights its popularity amongst practitioners [46-48]. Homer® software allows:

- User-friendly GUI, quick guidance
- A huge number of advanced component models
- Comparatively fast time intervals (8760-time increments in less than one minute).
- Sensitivity variables.

2.5 Software used in Modeling of Hybrid Energy System

Software tools are mostly used in the hybrid systems for simulating, optimizing, and sizing of systems. Some of these tools used in existing literature are HOMER, RETScreen, HYBRIDS, HOGA, Hybrid2, SOMES, ARES, SOLSIM, RAPSIM, IPSYS, SOLSIM, and DESIGN PRO.
From all the software tools mention, HOMER has been considered as the most widely used tool used for simulation and optimization of hybrid systems. This tool is capable of simulating different energy sources and also performs sensitivity analysis to determine the robustness of the hybrid system. [51-55]. The advantage of HOMER over the other hybrid designing tools is that it is capable of combining multiple energy systems by making a comparative analysis based on technical and economic parameters.

3 Methodology

In this section, the researcher explains the methodology for comparison of electric battries and pumped hydro storage for the optimization of the solar PV plus storage system in rural Liberia (Southeastern Region). HOMER (Hybrid Optimization Model for Electric Renewable) was used for the techno-economic optimization of the system. HOMER is designed by National Renewable Energy Laboratory (NREL) for designing renewable hybrid systems and to assist in the comparison of different generation sources in terms of cost and technical parameters in a poly-generation system. It also provides a cost comparison of grid extension and off grid standalone systems, which is a key objective of the researcher.

3.1 Interviewed Participants Selection

The study selected participants using purposive sampling technique- An ideal non probability sampling technique relevant to the research since the information required was from technocrats, and participants engaged in clean energy and rural electrification issues in the region and nation as a whole. This made the researcher to ascertain in-depth knowledge that is needed to answer the research questions. The selection of participants was done through preliminary literature search initial data collection.

The researcher first conducted a literature search on the actors involved in renewable/sustainable energy initiatives in the nation and specifically the region. This search focused on institutional arrangements, forecasting of the rural energy sector in Liberia, projects relating to clean energy and sensitive documents, as well as a review of NGOs that are currently working on sustainable energy issues in the Liberia.

Next visits was made to the five counties within the region, with remarkable stops at the hubs of the Liberia Electricity Cooperation in Partnership with LRREA and Endev Liberia to get on the field experience which couldn't be attained anywhere else.

A list of all actors and agencies working on sustainable energy issues was requested from the office of Rural Electrification-LEC and the Liberian Archieves. This list was reconciled with the list obtained from the literature search to obtain the list of participants for the research. In the course of data collection, the respondents were asked to mention other actors that they work with on sustainable energy issues in the municipality. This process led to the emergence of some new actors who were not captured in the initial list generated.

According to the Liberian National Achieves (LNA), the below mentioned are the entities that were actively involved in the provision, transmission and expansion of sustainable energy and rural electrification in the nation: Rural Electrification Department of LEC, Liberia Rural and Renewable Energy Agency, Energizing Development/GIZ, Power Africa, EPA, UNIDO Energy Project etc.

3.1.1 Sources and Type of Data

Data for the study were obtained from both primary and secondary sources. Primary data were obtained through interviews. The data were collected from all the actors mentioned above. Actors were interviewed to obtain primary data on their engagement in sustainable energy initiatives, their participation and nature of involvement in sustainable energy initiatives. Secondary data, on the other hand, were obtained from both published and unpublished sources. These sources include institutional reports and other studies related to the subject matter and the region under study. When gathered, the later part of the research used HOMER Pro software to analyze the data and make comparative analysis of energy scenarios as detailed explained in the next sections of this research and the chapter four (4).

3.1.1 Privacy Release and Ethical Considerations

For professional and ethical purposes, the researcher utilized the template letter of PAUWES from the LMS, which gave him the clearance to solicit information from the governmental and non-governmental institutions and participants of this research. All data collection instruments were devoid of any personal information such as names or contact addresses. Each data collection instrument has a preamble which introduces the main aim of the research and indicates a statement of assurance that data gathered is purposely for academic work and that respondents were assured of the privacy release clause, confidentiality and anonymity. In instances where pictures and audio recordings were made, the researcher sought verbal consent from all respondents before proceeding with such recordings.

3.2 Data Analysis Technique (HOMER Pro Usage)

HOMER has extensively been used in many studies for investment decisions in Africa some of which have been mentioned in detail in the literature review section [38-44]. Being different from most time-series simulation software, HOMER reduces complexities by providing access to worldwide database for Solar PV irradiation, the ability to design and choose industrially available components and the option to model a PHS along with other technologies. [45]

Figure 6 displays the data analysis input flow that is adopted in this study. Primary Energy resources used in this study (Solar, Electric Batteries and PHS) is firstly modeled based on the techno-economic parameters listed in Table 1. The meteorological data such as the geographic solar irradiation is exported from the NREL database and a time series input of load profile is fed into the system. After which optimization of the system architecture in terms of least cost and technical viability is performed. A number of sensitivity variables are identified based on the optimal configurations that have the most impact on the system output. The system is then checked for robustness by varying these sensitivity parameters to assess the change in optimal configuration, after which final system architecture is obtained. See results presented in section 3.3 and above.

An Endev/GIZ grid connected PV system with storage is studied to analyze feasibility of renewable Energy Storage integration (either using PHS or batteries) for the urban case. The Urban case was considered to make concise comparison with the rural electrification comparison for integrating RE in the grid.

The below mentioned scenarios was modeled for analysis:

i) Grid connected PV

ii) Grid connected PV + pumped hydro storage (PHS)

iii) Grid connected PV + electric batteries

For the rural case, the Off Grid PV system with storage primarily addresses the use of storage technologies with PV for rural applications in very remote villages. Since in such cases the PV arrays are not grid connected, this part of the study deals with the economic comparison of grid extension breakeven points and also explores the following configurations:

i) Solar PV + pumped hydro storage (PHS)

ii) Solar PV + electric batteries

The steps below in the methodology are further explained in detail later in this chapter

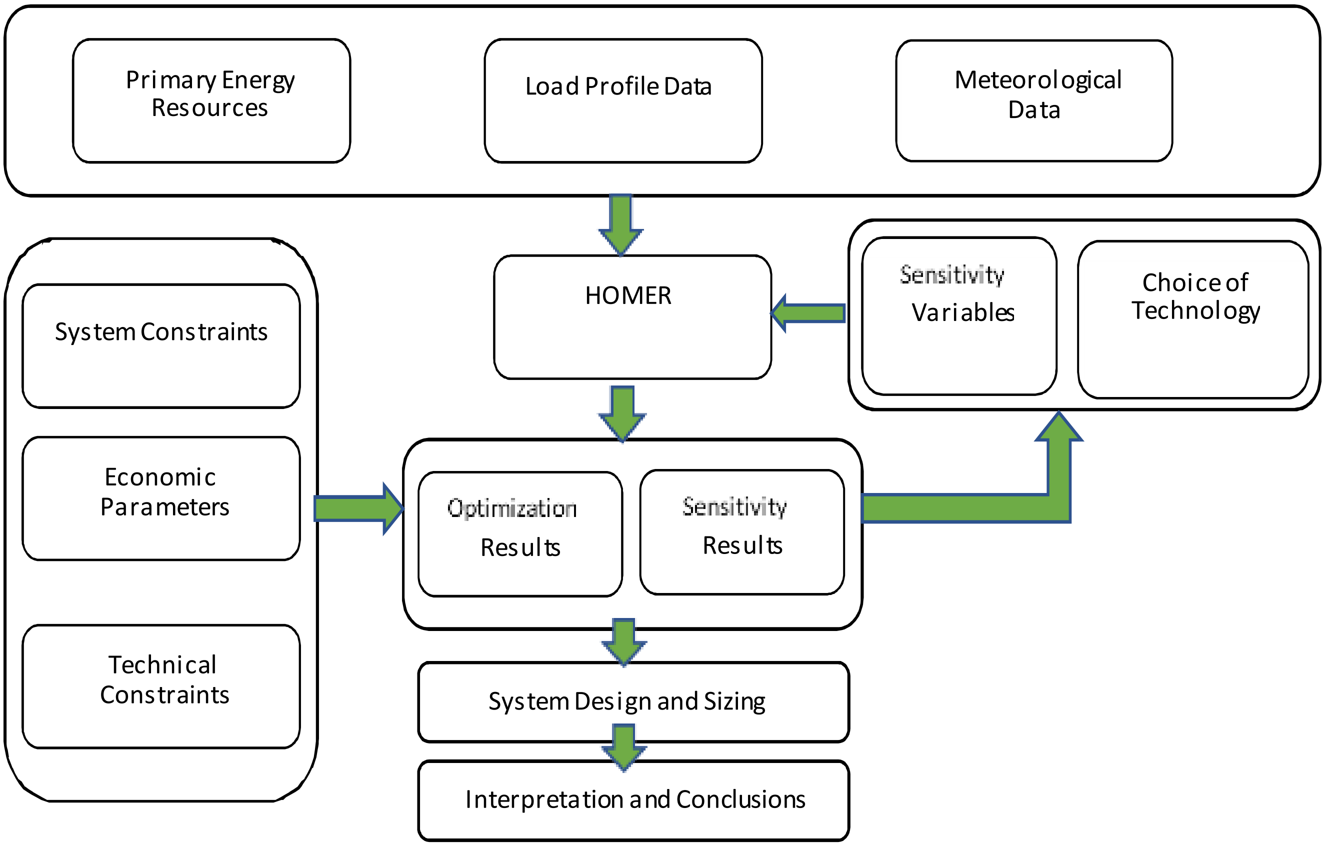


Figure 8: Methodology Flow of the Study

For performing the analysis, load profile of the different consumers (rural and urban) as well as load profile for other energy usage was determined.

3.3 Load Profile Assessment

To have an accurate idea of the content of this topic in relations to COE in Liberia and for comparison purposes, the load profile analysis was performed for the following two cases:

3.3.1 Urban Population (Grid Connected)

3.3.2 Rural Population (Off Grid)

The urban and rural population load profile was further divided into residential and non-residential loads as shown in Figure7.

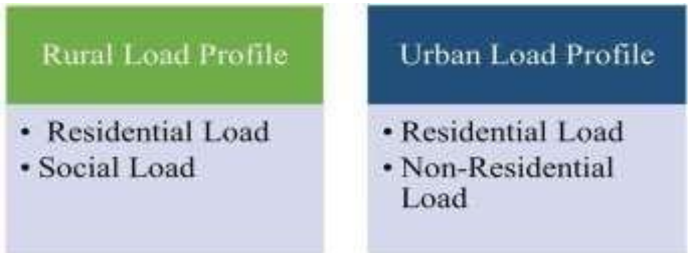


Figure 9. Load Profile Components

3.3.1 Urban Load Profile

The urban profile in this study was modeled for the city of Monrovia, the capital of Liberia which has a population of approximately 1million (939, 524) people. Monrovia receives about 900 mm of rainfall annually, which is spread over from May to October. The minimum average temperature in the cold season (December to January) is 16 degree Celsius. The maximum average temperature during the hot season (March to May) is about 43 degree Celsius.

3.3.1.1 Residential Load Profile

In Monrovia, electricity consumption for residential consumers is predominantly lightening (58%) with electric fans (22%) and air-conditioning (12%). Other miscellaneous consumptions are accounted for by washing, cooking, ironing etc. The figure below accounts for what goes on in the city of Monrovia as accounted for by the Liberian Electricity Cooperation.

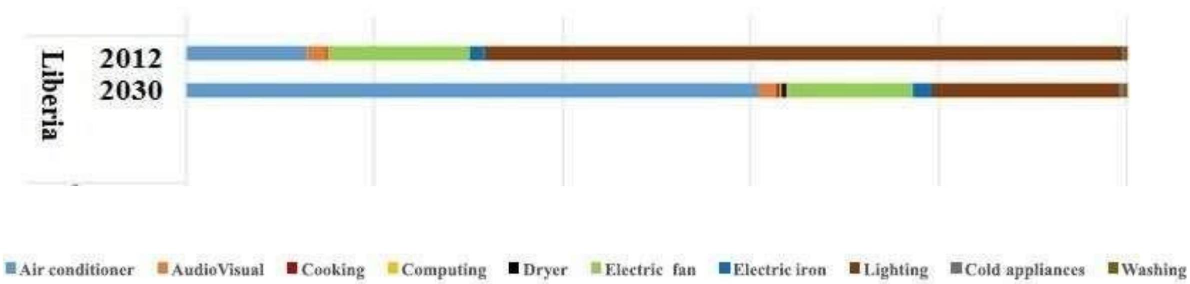


Figure 10. Residential Consumption in Liberia

A fatal challenge in estimating the load profile in developing countries is the lack of quality data as extensively experienced by the researcher during the scope of this study. However, studies such as done by Adeoye et al [2] that provide modeling and forecasting guidelines for hourly residential demand profile in West African countries provide realistic assumptions that can be used to model the residential urban and rural load demand profile. Many other researchers have performed models for hourly electricity demand for both developing and developed nations [46-48]. The degree of relative error for the actual forecasted electricity demand for 2013-2017 performed by Adeoye et al [2] ranges from (-7% to 2%) Models of such nature are typically based on behavioral, economic, social and meteorological data to model household electricity demand. However, in this study, after data collection, the results from a bottom-up analysis and general parameters for social economic factors are found in the table below.

Table 1. Assumptions-Values for Load Profile Modelling

General Parameters	Urban Case	Rural Case
Population (Monrovia)	1 million	45000 [25]
Number of inhabitants (per household)	5	7
Daily energy consumption pattern for households	1/3 energy consumed during daytime and 2/3 during evening and night	1/3 energy consumed during daytime and 2/3 during evening and night
Electricity Consumption per capita	45 kWh per year	35 kWh per year

There are basically two seasons in the West African countries dry season and rainy (wet) season. The seasonal variability analysis performed by EnDev for 2017 suggest little difference in the demand profile of both the seasons as shown in figure 11.

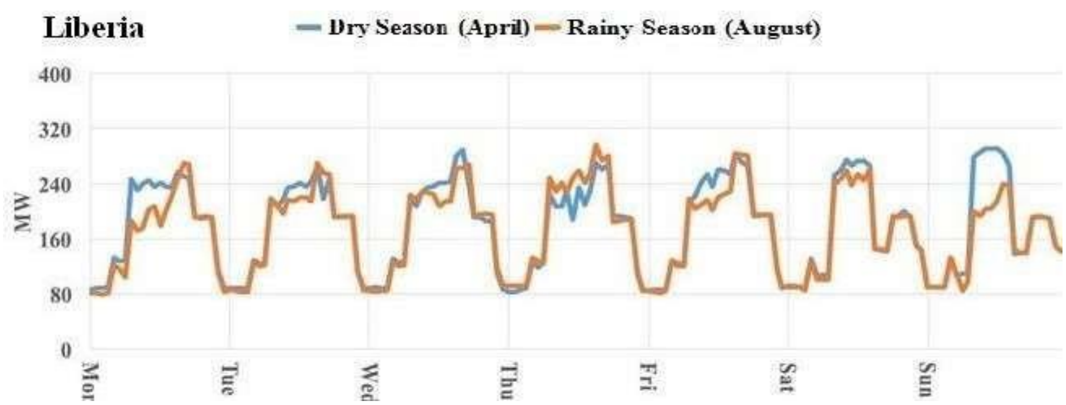


Figure 11. Seasonal Variation of Electricity Consumption in Liberia (2017)

This is mainly due to the low temperature variability during the two seasons as shown in Figure 12.

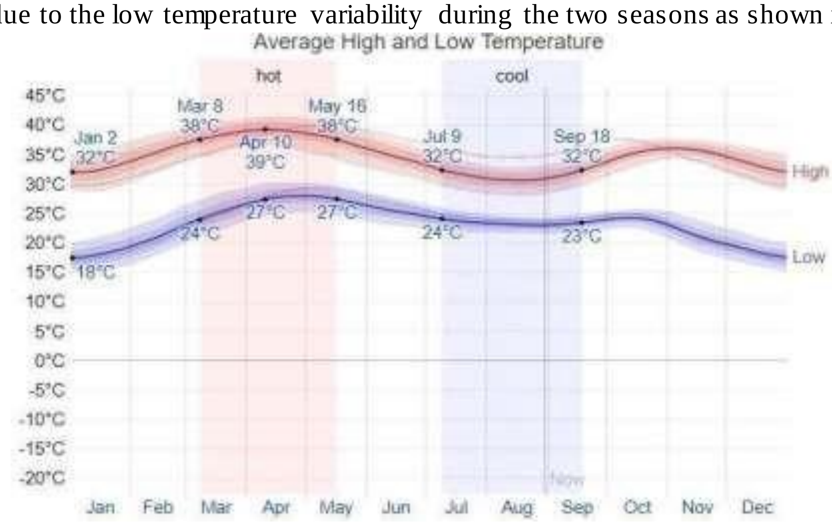


Figure 12. Yearly Temperature Variations in Monrovia [29]

Therefore, based on the general parameters mentioned in Table 1 and limited variability of seasonal effects the hourly residential urban residential load profile was modeled as displayed below in Figure 13.

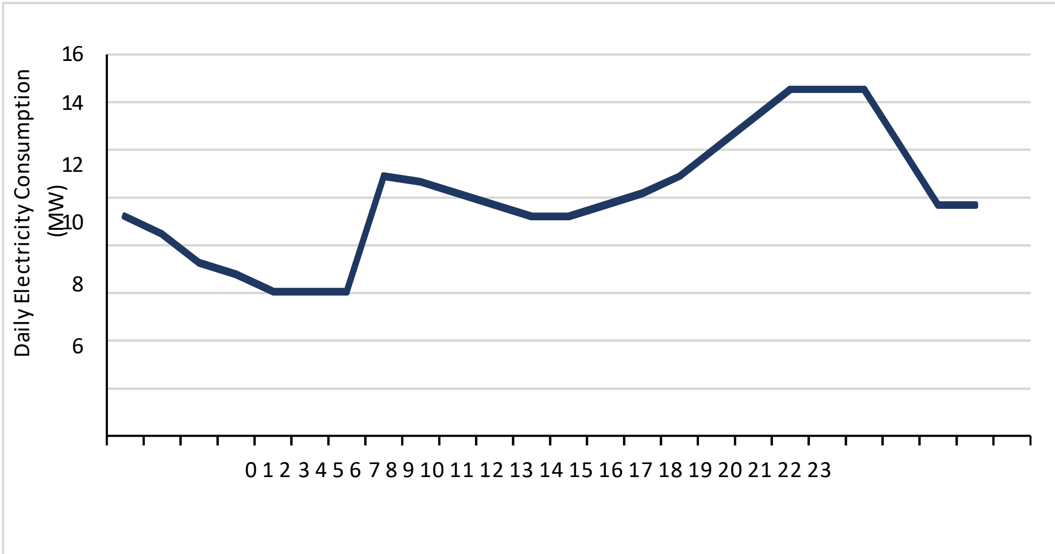


Figure 13. Urban Hourly Residential Electricity Load Profile (Author's analysis, based on assumptions in Table 1, see Appendix A1)

3.3.1.2 Non-Residential Load Profile

The non-residential load in the urban profile consists of industrial, commercial and services demand sector as modeled by [2]. The overall non-residential load demand in the urban setting was synthesized using typical non-residential load profiles in the West African countries and the overall energy consumption [2].

The overall non-residential consumption in 2017 was found to be 720 GWh with a relative error of 1.2 % [2]. The per capita nonresidential demand was found to be 35 kWh per capita, and it is assumed that 2/3 of the energy is consumed during daytime and 1/3 is consumed during evening and night.

The synthesized non-residential profile for Monrovia is as shown in Figure 12; the average non- residential consumption is 230 MWh/day for a population of 1 million people with a peak demand of 26 MW.

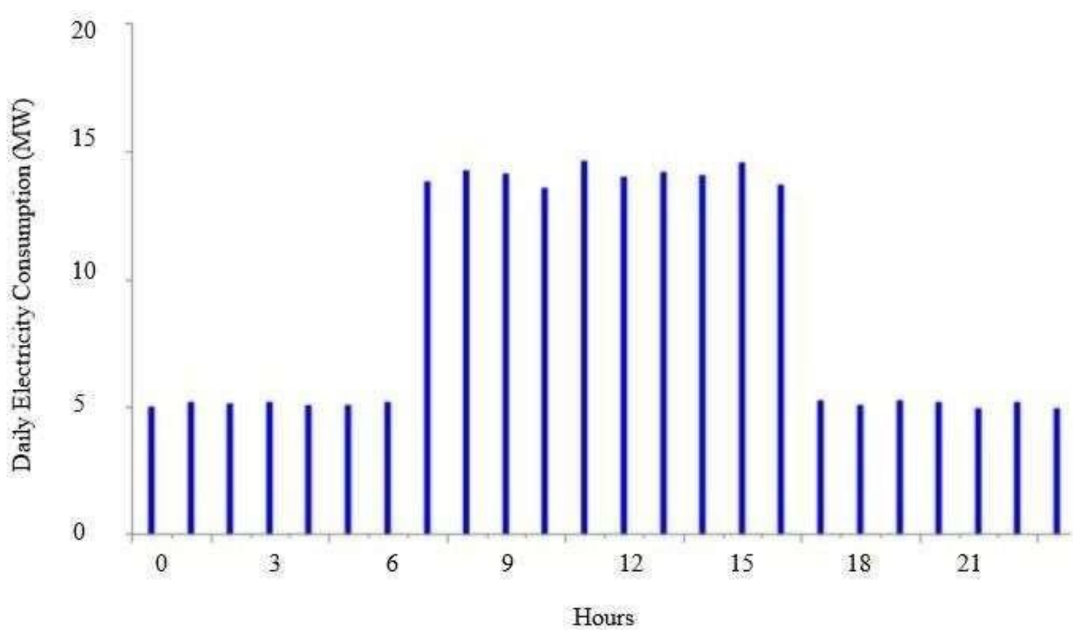


Figure 14 Urban Non-Residential Daily Load Demand (Author's analysis, based on assumptions in section 3.3.1.2)

3.3.2 Rural Load Profile

A village (Cavalla) located near Harper in the Southeastern Region (4.3760° N, 7.7009° W) of the nation was used to model the rural load profile of Liberia and Maryland County is considered in this research.

3.3.2.1 Residential Load Profile

Cavalla has a population of 40,000 inhabitants and 5672 households assuming seven inhabitants per household. In Cavalla, you per capita electricity consumption in the rural household were found to be around 35kWh per capita per year. Similar pattern of consumption as evident in Table 1 for residential load profile of urban areas was used and the residential load profile was modeled and shows the below graph in Figure 13.

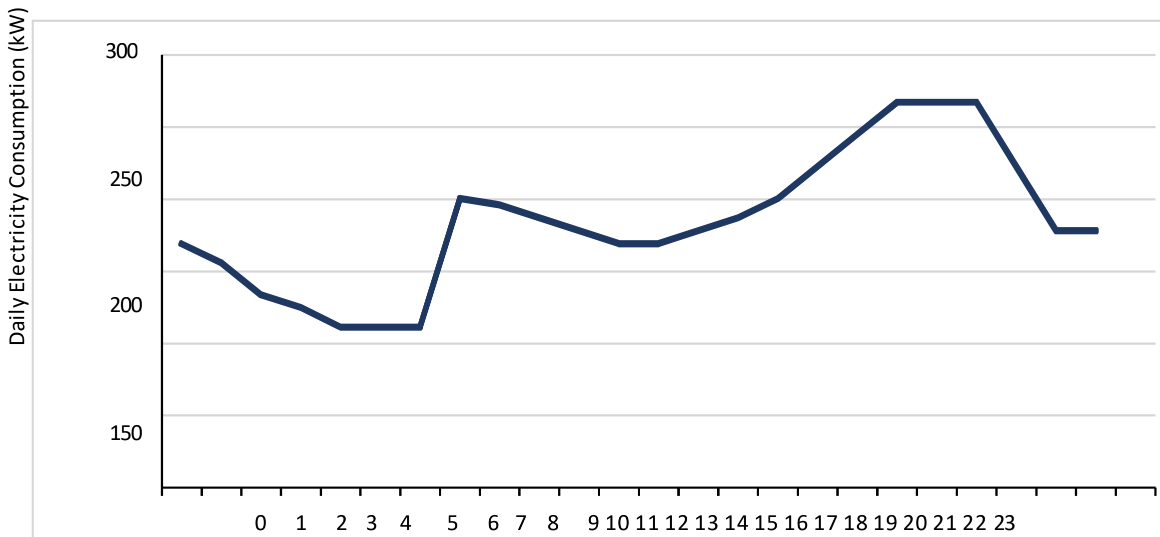


Figure 15 Rural Hourly Residential Electricity Load Profile (Author's Analysis, see Appendix A1)

Peak hours in Liberian rural settlements often occurs in the morning and late evening as a consequence of the social life of inhabitants. This is due to higher occupancy which is simply the probability of having more occupants at the same time during those times and the use of lighting, electric fans, water pumps and other electronic appliances. The demand during the day remains relatively flat due to a lower occupancy.

3.3.2.1.1 Social Load Profile

Social load consumption here is regarded as the load for societal use such as health centers, public lighting etc. The parameters and assumptions considered for the social loads for a typical village in West Africa are listed in Table 2.

Table 2. Social Load Assumptions [4]

Social Loads/Assumptions	**Values**
Social Center	2 kW
Health Center	5 kW
Hospital	15 kW
Electricity consumption pattern for social loads	2/3 energy consumed during daytime and 1/3 during evening and night

Figure 14 shows the daily values for a typical social load profile for the village, the average consumption is 550 kWh/day and the peak load is 62.55 kW.

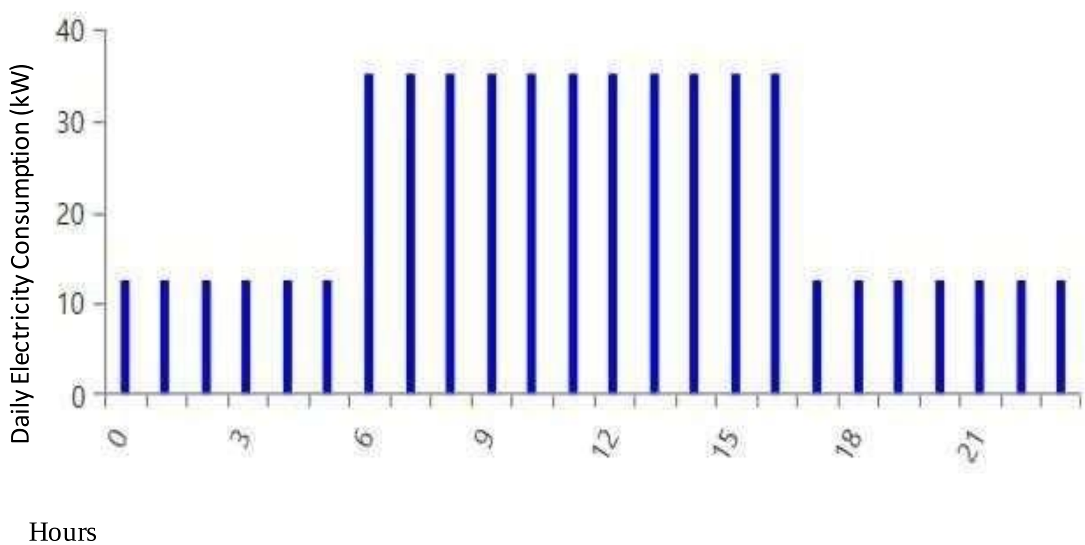


Figure 16 Social Load Profile for Rural Village(Author's Analysis based on Assumptions from Table 2)

3.4 System Configuration

The system has been designed such that it consists of a residential and non-residential load (social load in case of rural off grid architecture) connected to the PV array, storage devices (pumped hydro storage and electric batteries) and a converter system. Each individual system component is explained in detail in the next section of this chapter. Figure 15 (a) shows the grid connected system architecture where the DC components (electric batteries, PHS and solar PV) are connected on the left whereas the AC grid and the AC residential and non- residential load is shown connected on the right side. Similarly, Figure 15 (b) shows the off grid rural system architecture, since the system is not grid connected, a grid connection is not shown. Both storages are shown connected to the DC grid however; in practice only one of them will be used based on the optimal design configuration.

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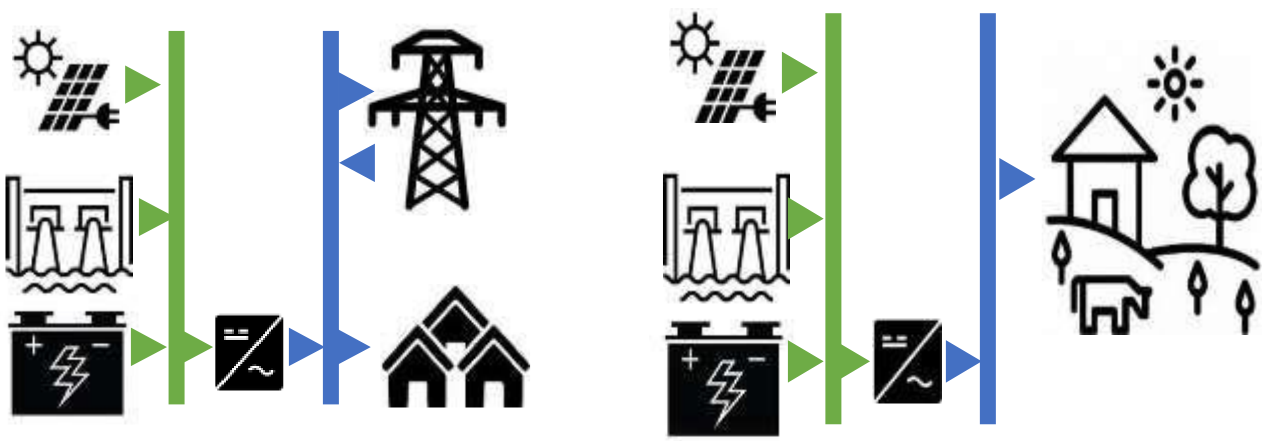

Figure 17 (a) Grid Connected Urban System Architecture (b). Off Grid Rural System Architecture

Based upon system designed and architecture in the above figure, the system architecture for all the scenarios of urban and rural cases are designed in HOMER. As aforementioned in the scenarios, to analyze the feasibility of grid extension, the off grid rural system is shown connected with the grid. Figure 16 (a) shows the off-grid system architecture as modeled in the software and Figure 16 (b) shows the grid connected system architecture. These specifications are listed in Table 3 for the cost parameters and load values are taken based on the analysis performed in section 3.3.

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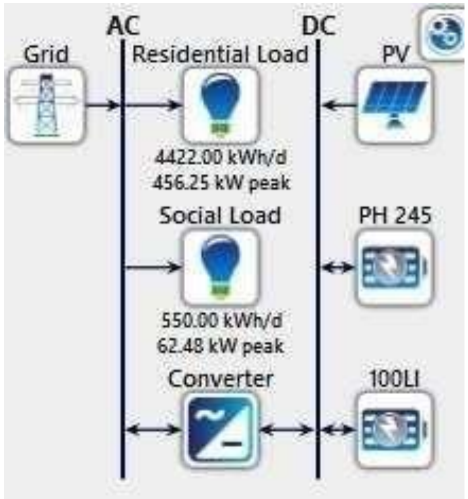

Figure 18 (a). Off Grid System Architecture (HOMER) (b). Grid Connected System Architecture (HOMER)

3.5 Component Specifications

In this section, detailed information about the renewable energy resources is modelled for the system; and each individual component are being discussed in the subsections below. For gathering input parameters the table below shows a concise summary of how the researcher dealt with each parameter.

Table 3. Summary of Input Costs Parameters

RE Equipment	CAPEX	Operation and Maintenance	Expected Lifetime	Replacement Cost (where applicable)	Efficiency	Source
PV System	850-2000 €/kW	10 €/kW/year	25 years	850-1500 €/kW	20.4 %	[49] [50]
AC DC Converter	650 €/kW	0	20 years	600 €/kW	90 %	[49]
Electric Batteries	200 €/kWh	5 €/kWh/year	10-12 years	200 €/kWh	90 %	[51]
Pumped Hydro Storage	800 €/kW[3]	40 €/kW/year	25 years[4]	800 €/kW	81 %	[6] [7]

3.5.1 PV System

The studies uses mono-crystalline SPR-E20-327-C-AC module which was manufacture by Sun-Power [52]. In order to gain in-depth understanding of the general and technical specification of the system, kindly view appendix B1. Pricing and financial costs range listed in the above table indicates capital costs of PV for community versus a Utility scaled PV system. The lower value is for the utility scale classified by Lazard's [51] for the capacity of (>5 MW) which was used in the modelling for the urban case grid connected utility scale PV in this analysis. The upper value is for the community scale classified by Lazard's within the capacity of (1-5 MW) which was used for modelling the rural off grid case in the analysis. Understanding that the price of PVs change frequently, the report was used as a reference and a sensitivity analysis was also performed to see the change in the optimal configuration for both urban and rural cases. To reduce uncertainty a similar approach is used in the literature such as adopted by [45].

There is a significant capital cost difference between the utility scale grid connected system and the off-grid system; the capital cost considered for the utility scale PV is 850 €/kW whereas for a community scale PV it is taken as 2000 €/kW as listed in Table 3. This difference is mainly due to the differences in the EPC (Engineering, Procurement and Construction) costs, developer overhead and net developer profit- all of which are termed as "soft costs" that are much lower for utility scale PV as compared to commercial scale PV as given by NREL cost benchmark Q1, 2018 report [33].

Accounting for real operating conditions as compared to the conditions under which the panel is originally rated, a derating/ deppreciation factor of 0.95 was considered for the study and is used while evaluating operational efficiency of the panels in the analysis. The site-specific parameters such as the cost of land acquisition are not taken into account for this study.

4 *The capital cost here does not include excavation and construction costs for two new reservoirs which is discussed in detail in section 4.3.4*

5 *Taken here as the lifetime of the project which is 25 years, in reality it is 40 -100 years for pumped hydro* [14]

5.1.1 Solar Energy Resource

The data value for solar radiation were downloaded from NREL National Solar Radiation Database at the coordinates of 6..3156° N, 10.8074° W (Monrovia, Liberia). The annual solar radiation found to be 5.64 kWh/ m /day while the average clearness index was found 0.6 indicating a high potential of solar energy generation through PVs. Figure 17 displays the average clearness index and solar radiation for different months.

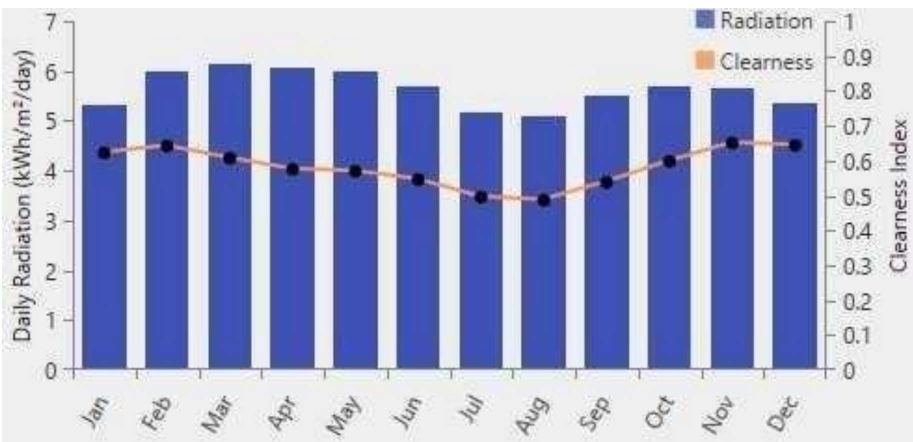

Figure 19. Monthly Daily Average Solar Radiation and Clearness Index for Monrovia [53]

5.1.2 AC DC Converter

As a measure of ensuring continuity of flow of energy between the DC components (solar PV, electric batteries, pumped hydro storage) and the AC components (grid, AC loads, a bi directional AC-DC converter is used. The capital cost, replacement cost, replacement cost and lifetime for 1 kW system are 650 €/kW, 600 €/kW and 20 years respectively[49].

5.1.3 Pumped Hydro Storage

Pumped hydro capacity is utilized to store overabundance power from the PV clusters at times of off-peak generation to meet the demand for the electric load, amid periods of abundance power generation, the overflow PV power is utilized to pump water from a lower supply to an upper supply additionally vitality is put away within the electric batteries at the time of excess power generation. During times of a supply –demand imbalances, water is permitted to run through a turbine creating power or alternatively energy is supplied through a battery. There are 6 major rivers within the nation (St. John, St. Paul, Cestos, Cavalla River, River Gee, Mano) with an evaluated theoretical potential capacity of 4478 MW. The longest one is the Cavalla River 515 km (320miles), found within the Southeastern region of Liberia which borders with Ivory Coast. The other principal rivers run north to south within the central region Western and Central and Southeastern regions respectively.

Planned future hydro projects are mostly located on the Mano River, River Gee and the Kpatawi Waterfall with a capacity of around 60 MW. The city of Monrovia utilized in the urban section of this study is located just 10km away from the Mt. Coffee Hydro Dam which provides most percentage of its hydro-electricity power.

Where pumped hydro could be a develop innovation with a really long lifetime low self-discharge and a large storage capacity capability [46], it does have its potential restrictions. . One of the major challenges with Hydro is being the difficulty in identifying geographically suitable locations. Several propositions have been proposed in the literature to tackle this; like the use of old coal mines as reservoirs or the use of FLES (Flat Land Large Scale Electricity Storage) [54]. FLES does not depend on common relief and height to store gravitational vitality but but creates two artificial storage reservoirs. The recommendation of PHS with no existing reservoirs is additionally proposed within the literature and cost estimates for excavation and civil works have been suggested. For example; one study by the "Oak Ridge National Laboratory, Sep 2016"[55], developed costs models for three test cases:

- Test Case 1: New upper and lower reservoirs
- Test Case 2: Refurbishment of upper and lower reservoirs
- Test Case 3: Existing upper and lower reservoirs

Concurring to [55], the costs associated with creating new reservoirs come out to be (30 €/m^3). This incorporates costs of leveling and grading, drainage, erosion control, soil excavation, rock excavation and geomembrane. As specified in Table 3 the capital costs related with PHS given that there exists two capacity supplies with an rise of 100 meters and a capacity capacity of 1000 cubic meters is 800 €/kW with a turbine productivity of 81 %.

When extra costs of building modern supplies (upper and lower) are included, the capital costs increment enormously by more than 400 % and the gracious development costs as a component of capital costs turn out to be nearly 80 %. The results are formulated considering that new reservoirs need to be constructed and based on the parameters listed in Table 3. The following parameters are not taken under consideration into this study that could potentially have an have an effect of the ultimate costs.

5.1.3.1 Costs for construction of pipelines for the transportation of water from the available water bodies to the point of construction of PHS system in the case when two new reservoirs need to be constructed which could vary considerably based on the settlement taken for electrification.

5.1.3.2 Costs for land acquisition for the construction of PHS system.

3.1.1 Electric Battery Storage

Given the recent decrease within the battery costs it is beneficial to think about the achievability of comparison of batteries and pumped hydro as a capacity. For this think about, the financial parameters for “Infront of the Meter” battery an application for utility scale were considered and primarily based on the most recent adaptation of Lazard’s levelized fetched of capacity. A single unit of 100-kWh of a Li-ion battery was utilized within the show whose capacity scales up as per the demand input of the model. Based on the least cost principle in combination with solar PV, the number of batteries and the quantity of storage that satisfies the load demand without capacity shortages was determined. The capital cost, replacement cost, operation and maintenance cost, lifetime and efficiency are 200 €/kWh, 200 €/kWh, 5 €/kWh/year 10 years, 90 % respectively [5].

3.6 Assessment Criteria

In this section, description of the main parameters is provided and on which different optimal configurations were compared for their feasibility.

3.6.1 Net Present Cost

The objective function is the minimization of cost of the whole system [56]. The model optimizes feasible system architectures for the given scenarios of rural and urban cases. The feasible configurations are ranked in terms of Total Net Present Cost (NPC). The NPC is the present cost of all the system costs incurred over its lifetime and is measured in euros. These costs include all capital costs, O&M costs, fuel costs, replacement costs and costs associated with buying electricity from the grid. The revenues include the salvage value and grid sales revenue [38]. The objective function is mathematically expressed in equation (1). The function is constrained by the inequalities (2) – (5):

$$min(C_{NPC,i}) = \sum_{all\ elements}\left[-R_{0,i} + \sum_{t=0}^{N}\frac{R_{t,i}}{(1+d)^{t}}\right] \quad (1)$$

Subjected to the following constraints:

$$P\text{shedding} \leq 0.05\ .\ P\text{Soad} \quad (2)$$

$$f\text{PV} \geq 0.15\ .\ E\text{gen} \quad (3)$$

$$r\text{load,t} \geq 0.10\ .\ P\text{Soad,t} \quad (4)$$

$$r\text{peak Soad} \geq 0.10\ .\ P\text{Soad} \quad (5)$$

Where

R0 is the initial investment [€]

N is the project lifetime

R_t is the net cash flow for each component (i.e., revenues minus costs incurred) [€]

d is the discount rate [%]

i represents individual components $P_{shedding}$ is the load not served [kWh] f_{PV} is the PV fraction [%]

E_{gen} is the electricity generation [kWh/year]

$r_{load,t}$ is the input operating reserve as a percentage of load in the time step t [%]

$P_{load,t}$ is the load in timestep t [kWh]

$r_{peak\ load}$ is the input operating reserve as a percentage of annual peak load [%]

The objective function focuses on the minimization of total net present cost which is the present value of all the costs the system incurs over its lifetime and is mathematically shown in equation (6) as follows:

$$NPC = \frac{C_{ann\_tot}}{CRF(d, N)} \tag{6}$$

Where

C_{ann_tot} is the total annualized cost of the system. The annualized cost of a component is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component. *CRF(d,N)* is the Capital Recovery Factor

The total annualized cost of the system is as given in (7):

$$C_{ann\_tot} = C_{ann\_cap} + C_{ann\_rep} + C_{ann\_OandM} + C_{ann\_fuel} - R_{ann\_salv} \tag{7}$$

where C_{ann_cap}, C_{ann_rep}, and C_{ann_OandM} are the annualized capital, replacement costs, and operation and maintenance costs of all components of the system respectively. C_{ann_fuel} (the cost of fuels for the generators is considered zero in our case).

$R_{ann,salv}$ represents the annualized total salvage value, that is the value remaining in a component of the power system at the end of the project lifetime [38]. The salvage value is calculated as follows:

$$R_{ann\_salv} = C_{ann\_rep} \cdot \frac{(reN)}{N_{coNp}} \tag{8}$$

Where N_{rem} is the remaining life of the component in years at the end of the project which is given as:

$$N_{rem} = N_{comp} - (N - N_{rep}) \quad (9)$$

Where N is the project lifetime [years]

N_{comp} is the component lifetime [years]

N_{rep} which is the replacement cost duration in year

A Capital Recovery Factor (CRF) used in (6) converts a present value into a uniform annual cash flow series over the project lifetime (N) specified at discount rate (d) given in (11). $CRF = (1 + d)N - 1$ (11)

The discount rate in this project was taken as 5 % and a lifetime of 25 years was taken for this project in accordance with the West African Power Pool recommendations [4].

3.6.2 Levelized Cost of Energy

The LCOE is the most transparent metric and commonly used tool to evaluate the cost of electric power generation when comparing different energy technologies [57] .The LCOE is a measure of the marginal cost (which is the cost required to produce one additional unit) of electricity over an extended period [58]. The LCOE can be defined by the average cost of electricity per kWh of useful electrical energy produced by a system; it can be calculated as the total annualized cost of producing electricity by the total load served [59].

Levelized cost of energy which is one of the output decision variables with units in €/kWh is defined as the average cost per kWh of useful electrical energy produced by the system [60]. Cost of energy is also an important assessment criterion for the study given the very high cost of production of electricity in Liberia or any West African state. However, the objective function is based on the minimization of NPC and COE is one of the outputs of the model which can be used in combination with NPC to decide the most optimal configuration. To calculate the COE, the annualized cost of producing electricity is divided by the useful energy that the system produces per year.

$$COE = \frac{C_{ann\_tot}}{E_{load} + E_{grid\text{-}sales}} \quad (12)$$

Where: Cann_tot is the total annualized cost of the system

[€/year] Eload is the total electrical load served [kWh/year]

Egrid_sales is the amount of energy sold to the grid per year [kwh/year]

3.7.1 Grid Extension

Due to exceptionally low electrification rate within the rural regions of Liberia, network expansion break even distance is a vital evaluation criterion for the achievability of standalone systems for rural population [61]. The breakeven grid extension distance (BGED) is the distance from the system to the grid at which the Net present cost of extending a grid from the nearest available distribution line and the standalone operation of the PV + storage are the same. The breakeven network expansion separate is calculated utilizing condition

$$D_{grid} = \frac{C_{NPC}.CRF(d,N) - C_{power}.E_{demand}}{C_{cap}.CRF(d,N) + C_{OandM}} \tag{13}$$

Where:

CNPC is the total net present cost of the stand-alone power system [€] CRF(d,N) is the capital recovery factor provided in equation (11) Edemand is total annual electrical demand [kWh/year]

Cpower is the cost of power from the grid [€/kWh]

Ccap is the capital cost of grid extension [€/km]

$C_{O \text{ and } M}$ is the operation and maintenance cost of grid extension [€/year/km]

If a settlement is located beyond this distance from the grid or beyond the reach of the grid, then it makes economic sense to have the standalone system for the electricity needs of that settlement. The required input parameters for calculating the breakeven grid extension distance are the capital cost, O and M cost for the grid per km and the grid electricity price. However, the Economics of Renewable energy Expansion in Rural Sub Saharan Africa [62] gives an estimate of the capital cost for 33kV medium voltage line to be around 30,000 €/km or more.

Therefore, since Liberia faces constant power shortages, grid extension may trigger additional investments in the centralized system that would further increase the price of grid extension per km. Considering this situation, the grid extension capital cost and operation and maintenance cost are considered as 40,000 €/km and 300 €/km. The grid electricity price is provided by the Power Africa and is assumed as 0.1-0.3 €/kWh.

4 Results and Discussion

Presentation of results in this session are primarily divided into two separate parts, Off-grid for rural electrification which the core of this research are presented and includes the optimization results, grid extension analysis and sensitivity analysis. Results of optimization herein highlights all system configurations that are technically feasible and give the lowest NPC as per the objective function in the equation mentioned in the previous chapter. Delving deeper, another optimization results for grid connected urban load is discussed followed by sensitivity analysis similar to the rural case scenario.

4.1 Off Grid

This section describes the results for the off grid rural load with standalone PV and energy storage systems (pumped hydro or electric batteries). First the optimization results are analyzed.

4.1.1 System Design Optimization for Rural Consumers

At the end of simulation performance, there was a total of 1603 cases which were analyzed out of which 779 has been found technically feasible, 823 cases has been infeasible with the constrain being the limited storage capacity. About 371 have not been considered since they had no sources of power generation. Evidently, there have been two categories with the least Net Present Cost (NPC) which has been found and listed in the Table 4.

Table 4. Results of Off Grid Scenario Simulations[5]

Result Specification	**Parameter**	**Unit**	**Category 1 (PV+PH)**	**Category 2 (PV+ Electric Batteries)**
System Architecture	PV	MW	1.7	2.2
	PHS	MW	1.4	0
	Electric Battery Storage	MWh	0	14.9
	Converter	kW	665	906

Economic Specifications	NPC	€	10.1 Million	12.3 Million
	Capital Cost	€	9.53 Million	9.29 Million
	COE	€/kWh	0.4	0.4

[5] *The results are calculated considering the capital cost of construction for both reservoirs*

The two categories are (PV+ PHS) and (PV + electric batteries) recorded as category 1 and 2 individually. The optimized PV capacity to meet an AC load of 1.81 GWh/year for category 1 is 1.6 MW with a pumped hydro ostensible capacity of 16 MWh and an AC-DC converter capacity of 665 kW. The net display fetched breakdown by component for category 1 is appeared in Figure 18 (a). The major parcel of the cost is the capital cost of pumped hydro since these calculations were obtained considering the civil construction costs of lower and upper reservoirs. The capital taken a toll of PV too includes 4.2 million euros of costs to the project NPC of 10 million euros over a lifetime of 25 years.

Figure 18 (b) displays the net display cost breakdown of category 2 (PV + electric batteries). Here the major component is the capital taken a toll of PV of around 2.9 million euros. It is curiously noted that the COE in both the cases is nearly comparable.

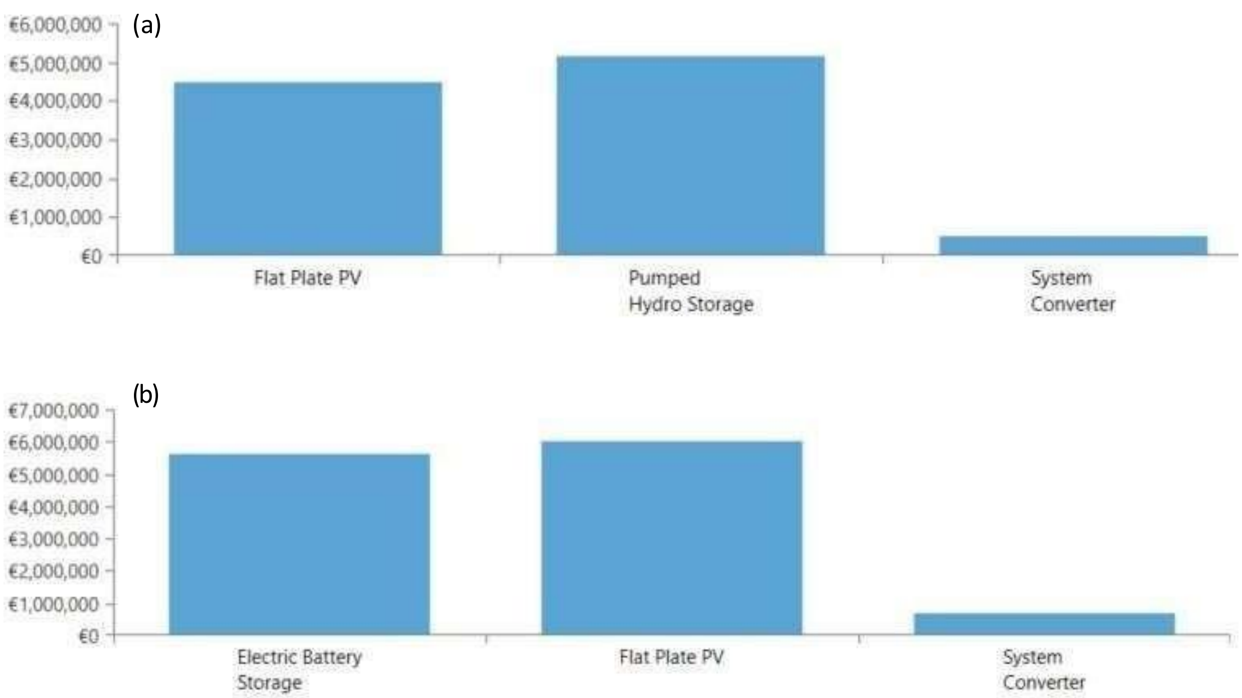

Figure 20 (a). Net Present Cost Breakdown of Category 1 (1.7 MW Flat Plate PV and 1.4 MW PHS) by Component with additional costs of excavation

(b). Net Present Cost Breakdown of Category 2 (2.2 MW Flat Plate PV and 14.9 MWh Electric Battery Storage) by Component with additional costs of excavation

An investigation was moreover performed to analyze the alter in ideal setups given topographical accessibility of upper and lower store without considering the cost of falsely creating it. The outline of the outcomes is given in Table 5.

Table 5. Results of Off Grid Scenario Simulations[6]

Result Specification	Parameter	Unit	Category 1 (PV+PHS)	Category 2 (PV+ Electric Batteries)
System Architecture	PV	MW	1.6	2.2
	PHS	MW	1.4	0
	Electric Battery Storage	MWh	0	14.9
	Converter	kW	523	906
Economic Specifications	NPC	€	6.15 Million	12.3 Million
	Capital Cost	€	5.54 Million	9.29 Million
	COE	€/kWh	0.25	0.4

The NPC in case of category 1 drops by 4 million euros and category 1 comes out to be the ideal framework arrangement. Thus, making PV + PHS a self-evident choice given the geographical appropriateness of PHS; the major commitment in this case comes from the capital taken a toll of PV in both the categories as appeared in Figure 19 (a) and Figure 19 (b).

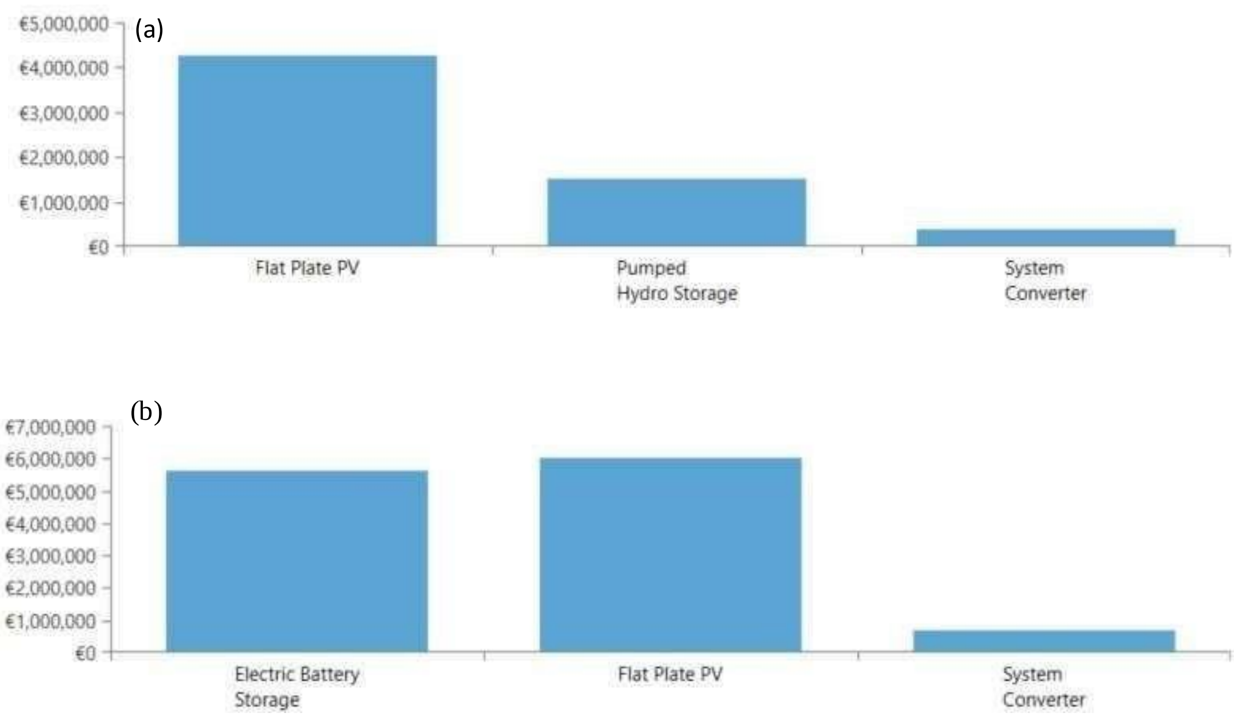

Figure 21 (a). Net Present Cost Breakdown of Category 1 (1.6 MW Flat Plate PV and 1.4 MW PHS) by Component without additional Costs of Excavation

(b). Net Present Cost Breakdown of Category 2 (2.2 MW Flat Plate PV and 14.9 MWh Electric Battery Storage) by Component without Additional Costs of Excavation

4.1.2 Grid Extension Breakeven Distance

As talked about prior, grid expansion breakeven is an imperative model to evaluate the possibility of an independent framework system. For the standalone PV+PH framework (category 1) for a town populace of 45,000 the breakeven network expansion separate comes out to be around 115 km as appeared in Figure 20 (a).

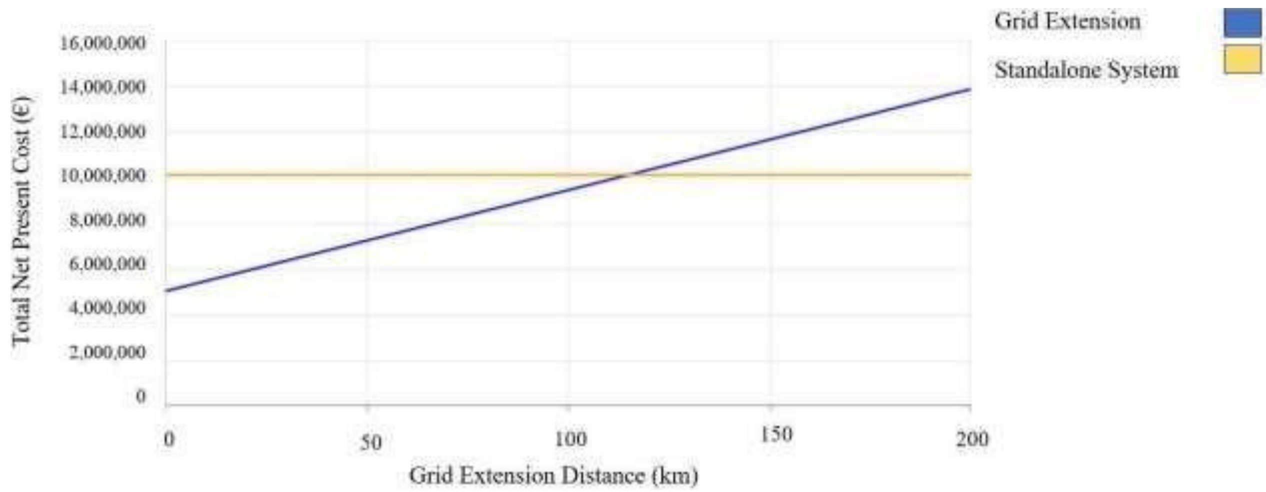

Figure 22 (a). Breakeven Grid Extension Distance for Category 1 (1.7 MW Flat Plate PV and 1.4 MW PHS) with Additional Costs of Excavation

The breakeven grid distance for PV + electric batteries (category 2) is much higher i.e. 160 kms; Figure 20 (b).

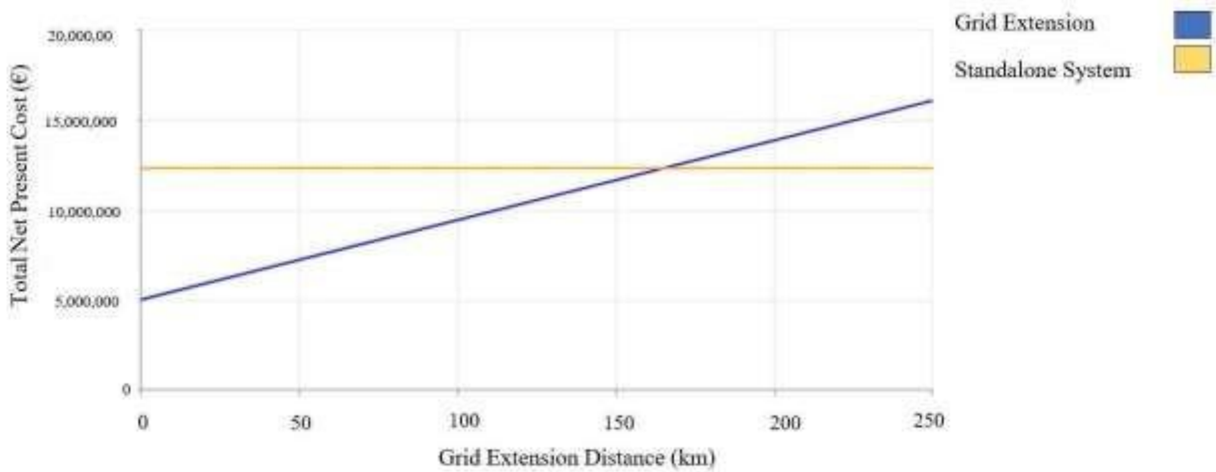

Figure 22 (b). Breakeven Grid Extension Distance for Category 2 (2.2 MW Flat Plate PV and 14.9 MWh Electric Battery Storage) with Additional Costs of Excavation

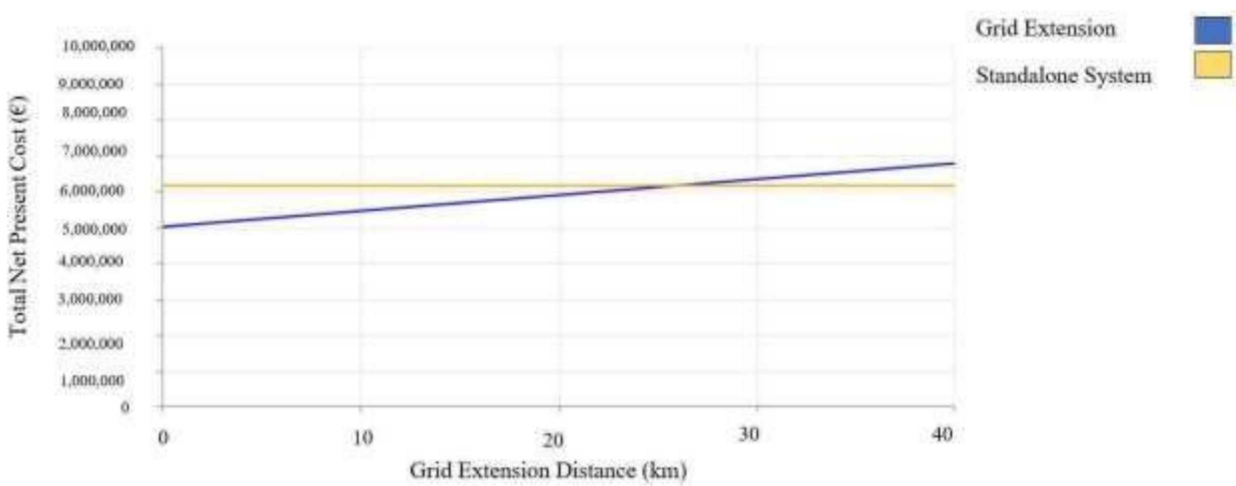

Figure 22 (c). Breakeven Grid Extension Distance for Category 1 (1.6 MW Flat Plate PV and 1.4 MW PHS) without Additional Excavation Costs

The separations are calculated considering costs of unearthing of both upper and lower stores. In the event that these costs are dismissed considering geographic accessibility of upper and lower supplies the BGED is evaluated to be 25 km as appeared in Figure 20 (c).We can see from these comes about that it gets to be progressively more doable to have a standalone framework for inaccessible zones that have geological accessibility for a PHS framework. In case both the reservoirs need to be developed; the populace should be a much more prominent remove (100 kms -160 kms) from the grid association. The sensitivity analysis examines how this distance shifts with the nearby populace of the settlement which gives a common system to survey the financial possibility of standalone systems.

4.1.3 Sensitivity Results

Sensitivity investigation gives a great understanding of the strength of a an energy model used. Given the ceaseless slant of diminish in PV costs and considering that the capital taken a toll of PV is the major component of NPC in all cases, an affectability investigation on the capital fetched of PV costs was performed with fetched multipliers of 0.25, 0.5, 0.75 and 1, and in this way the impact was watched on the alter in NPC and Taken a toll of Vitality as appeared in Figure 18. It can be seen that the NPC of the project nearly diminishes by a half with decline in PV CAPEX by 1/4th of the show price.

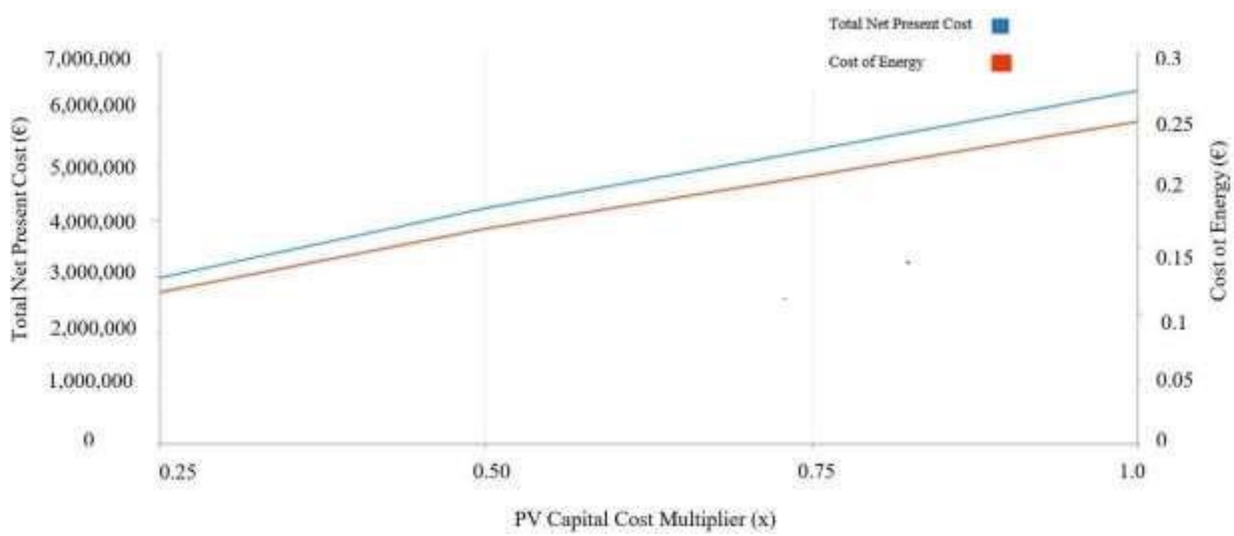

Figure 23. Sensitivity of COE and NPC with respect to PV Capital Cost

Figure 19 displays how the NPC involve with the alteration in demand. Table 6 shows the residential load demand of a settlement with their corresponding population and BGED. It can be seen that the NPC and PV capacity decrease in demand.

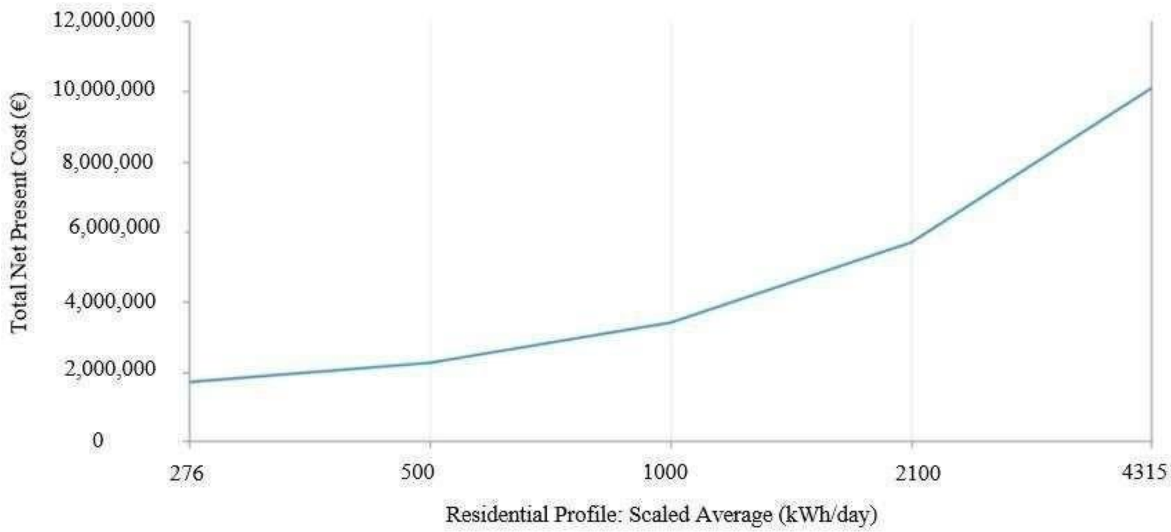

Figure 24. Sensitivity of NPC with respect to residential profile

A sensitivity analysis investigation for the breakeven network expansion remove was moreover performed with shifting populace sizes to analyze the achievability of standalone framework in terms of fetched for diverse sizes of rustic settlements. This would grant us bits of knowledge on how BGED can be utilized to-asses framework expansion achievability for shifting country populaces.

The ideal framework with shifting populace remains the same i.e. PV + PHS.BGED is provided in Table 6 for the same.

Table 6. Average Load Demand with Corresponding Population and BGED

Scaled Average Load Demand per settlement(kWh/day)	**Population**	**Breakeven Grid Extension Distance (km)**
4315	45000	115.29
2100	22500	67
1000	11250	41
500	5625	26.63
276.375	2812.5	19.44

The results are displayed in Figure 20. It is observed that it becomes more feasible to have a standalone system for a population of less than 6000 inhabitants that are at least 26 kms away from the nearest grid.

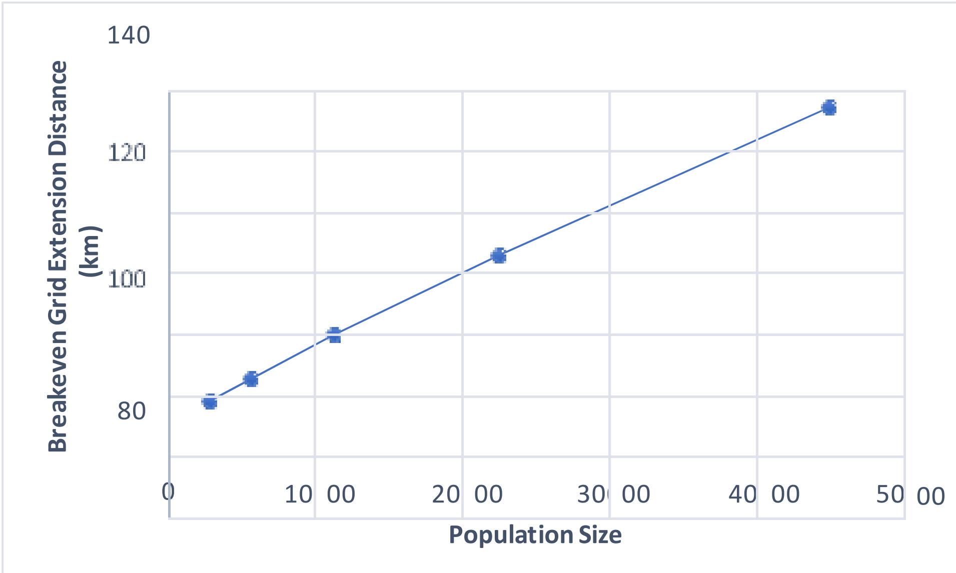

Figure 25. Sensitivity of BGED by Population Size

4.2 Policy Implications

Currently the rural electrification policies in Liberia is dominantly based upon the potential increase of the decentralized generation and distribution of power and the government ability to extend beyond the current reach of the national grid.

This study suggests that along with strengthening the national grid, future policies should also focus more on decentralized standalone systems especially for far off rural areas. In doing so, the rate of electrification in the country could be increased at a lower investment cost. Storage is a key component for standalone systems.

The potential barriers for practical implementation are high investment costs associated with capital cost of PV and geographical constraints on part of pumped hydro storage. It can be seen from the results for that the capital cost of PV is the most dominating factor in terms of net present cost for the whole system. Therefore it then becomes the responsibility of the national government to implement already existing policies as well as fast track projects ongoing in the renewable energy sphere of the nation.
This needs to be regulated especially by the LRREA and the EPA (Environmental Protection Agency) in collaboration with the Liberian Electricity Cooperation (LEC).

4.3 Limitations and Future Work

Additional studies have to be performed to address the confinements and limitations of this research; one being the distinguishing proof of potential destinations for geological accessibility of elated reservoirs for PHS due to inaccessibility of information. A GIS modeling of the country to locate prospective sites could be performed such as performed by Lu et.al [46] for South Australia. The outcomes from GIS displaying in combination with the break-even network expansion remove re-enactments from this study may give a much valuable experiences for sending of off network sun oriented also capacity arrangements.

Moreover, the site-specific parameters such as costs for arrive for land acquisitions; costs of pipelines for water supply to off grid settlements are not included that might impact the results for individual settlements. The scope of this study was limited to only two storage technologies with solar PV, future studies that look into other renewable electricity systems like PV plus generators, and other combinations.

Lack of accurate data for cost models for the specific context of Liberia is another limitation of the study. Provided the data becomes available, the results could be further improved to better fit the local context in future. Accurate load profile estimation is of great value in sizing and designing a power supply system.

Another limitation has been the difficulty of data collection especially during the time of the COVID pandemic. National lockdowns, offices closed etc. has been a major barrier to the researcher being in the field. There have also been problems of having biases of opinion from interviewees based upon his/her socio-economic status in community and their ability and willingness to pay for available electricity in the community.

5 Conclusion

The study deems it necessary for extended solar penetration in Liberia as a response to the challenges of low electrification rates in the country. It is seen that for grid connected systems, adding storage reduces the net present cost of the system by 8 % as compared to grid connected PV. The mere decrease in 8 % reduction of NPC over a lifetime of 25 years does not provide enough motivation with the present conditions, as other factors like the costs of land acquisition still need to be considered. The costs of deploying storage could be further reduced if future policies allow mechanisms such as energy arbitrage that allow stacking of energy storage benefits and revenues.

However, the study finds a definite need to add more solar energy to the present electricity mix Liberia. It is found that adding grid connected solar PV in an urban setting could reduce the cost of energy by half, making cheap electricity available for the local population and reducing the need of fossil fuel production. It would also increase the renewable fraction by more than 48%. The results for off grid scenarios indicate a grid extension breakeven distance of more than 26 kms for a population of less than 6,000 people using storage plus PV. Electric batteries remain quite expensive to be competitive with pumped hydro when new reservoirs need not be constructed, owing to high capital cost of batteries and a low lifetime. However, the costs increase drastically for PHS when excavation and civil construction costs are added for new reservoirs. The sensitivity analysis indicates that driving the capital costs of PV has the most positive effect on driving down the net present costs of both urban and rural cases. A support system that complements the capital cost of PV would prove to have the most effect on lowering the costs of electrification in Liberia.

Recommendations

The energy demand is rapidly increasing with time in Liberia. The government launched a program to integrate more renewable resources in the energy mix, to decrease the heavy reliance on conventional fuel, and to target the rural areas where grid extension is impossible to reach and seemingly extremely expensive for governmental undertakings amidst government's many responsibilities.
However, the program seems unambitious, insufficient, and less goal-oriented since the implementation is going slowly, and people still use diesel-based generators for electrification. Hence, the solution for off-grid will be the deployment of renewable energies and hybrid systems in order to increase the rate of energy access to rural areas. The following were recommendations for future work:

- ❖ Establishment of meteorological centers that possess on-site solar data and assessment studies for tapping into the hydro potentials that the nation is richin.

- Compare findings of this work with that of grid-connected Hybrid Energy System and include externalities.
- Compare findings on load estimation and environmental analysis in this work, with others done using other existing optimization tool for more robust findings on system sizing over the selected district.
- Encourage employees or student researchers of the LRREA to delve into researching for more authentic energy data for the nation as it was a primary challenge that the researcher has faced during the scope of this entire journey.

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7 Appendix

7.1 Appendix A

A.1: Residential time series hourly load profile data for urban and rural cases in Liberia used in this study

Hour	Energy Consumption (Wh)	Hourly Urban Residential Electricity Demand (kW)	Hourly Rural Residential Electricity Demand (kW)
0	38	9454.7408	169.2183723
1	35	8708.313895	155.8590271
2	30	7464.269053	133.5934518
3	28	6966.651116	124.6872217
4	25	6220.224211	111.3278765
5	25	6220.224211	111.3278765
6	25	6220.224211	111.3278765
7	45	11196.40358	200.3901777
8	44	10947.59461	195.9370626
9	42	10449.97667	187.0308325
10	40	9952.358737	178.1246024
11	38	9454.7408	169.2183723
12	38	9454.7408	169.2183723
13	40	9952.358737	178.1246024
14	42	10449.97667	187.0308325
15	45	11196.40358	200.3901777
16	50	12440.44842	222.655753
17	55	13684.49326	244.9213283
18	60	14928.53811	267.1869036
19	60	14928.53811	267.1869036
20	60	14928.53811	267.1869036
21	50	12440.44842	222.655753
22	40	9952.358737	178.1246024
23	40	9952.358737	178.1246024

A.2: Assumed parameters for occupancy dependent appliances for Liberia used in the bottom up analysis and compared with Adeoye et.al [2] study in West Africa

Appliances	Urban household power rating (W)	Rural household power rating (W)	Operating time
Audio-visual	125	200	7 h (+/-) 5 h
Cooking	2000	2200	2 h (+/-) 1 h
Computing	50	100	7 h (+/-) 5 h
Cloth dryers and washing machines	2000/1200	4000/3000	2h (+/-) 1 h consecutive
Electric Iron	750	1100	1 h

A.3: 2016 Assumed ownership rate for lighting bulbs for Liberia in urban and rural households used in the bottom up analysis of Adeoye et. al [2]

Lighting bulbs	Urban households	Rural households
Fluorescent lamps (%)	20	5
Incandescent lamps (%)	30	40
CFL lamps (%)	40	45
LED lamps (%)	10	10

A.4: 2018 share of employment categories in urban and rural areas for Liberia

Employment Category	Urban households	Rural households
Wage employment (%)	32.6	1.5
Non – farm enterprise (%)	41.8	48.3
Agriculture (%)	6.2	25.3
Stay at home all day/retired (%)	19.4	24.9

7.2 Appendix B

B1: Technical specifications of SPR-E20-327-C-AC mono-crystalline module manufactured by Sun- power

The following are the technical specifications of SPR-E20-327 solar module as mentioned in the Sun- power datasheet [47] and [27]

Item	Specification
Manufacturer	Sun-power
PV Module type	Mono-si
Module number	SPR-E20-327-C-AC
Module efficiency	20.4 %
Rated voltage (Vmpp)	54.7 V
Rated current (Impp)	5.98 A
Open-circuit voltage (VoC)	64.9 V
Short-circuit current (ISC)	6.46 A
Maximum system voltage	DC 600V
Power capacity	327 W
Power tolerance	+5 - 0 %
Power temperature coefficient	-0.38 % /°C
Voltage temperature coefficient	-175 mV/ °C
Current temperature coefficient	3.5 mA/ °C
Dimensions	46 mm x 1559 mm x 1046 mm
Operating temperature	-40 °C to +85 °C
Area	1.63 m^2
Weight	18.60 kg

THESIS APPROVAL

THESIS TOPIC: TECHNO-ECONOMIC ANALYSIS OF HYBRID ENERGY SYSTEM FOR RURAL ELECTRIFICATION IN LIBERIA

Submitted by:

Alvin Tepo Togba	Signature	Date

Approved by Examining Board

________________________	________________________	__________________
Name of Examiner	Signature	Date

Thesis/ Dissertation Advisors

________________________	________________________	__________________
Name of Advisor	Signature	Date

Institute Dean

__________________________	____________________	____________________
Name of Dean	Signature	Date

Pan African University

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Name of Rector	Signature	Date